ICNS 15
Malmö, Sweden 2025

ABSTRACT BOOKLET

Contents[1]

[1] The symbol * after the abstract identifier indicates presentation eligible for Young Researcher Award.

Oral

Plenary 1: The Isamu Akasaki Memorial lecture - Asif Khan

2025-07-07
09:00 - 09:50
Plenary 1: The Isamu Akasaki Memorial lecture - Asif Khan

The Isamu Akasaki Memorial lecture
III-Nitride Research: A Historical Perspective

Asif Khan[1]
[1] University of South Carolina

Abstract text: Over the past 50 years, III-Nitride technology has transitioned from significant materials growth, and doping challenges to devices leading to billion-dollar industries. This success in electronic and optical devices was built upon the foundational work of several researchers around the globe. This is a dynamic research area with constant new discoveries and technological advancements. In this presentation we will describe some of these contributions and how they impacted the field.

Plenary 2

2025-07-07
09:50 - 10:30
Plenary 2

Quantum Technologies with Hexagonal Boron Nitride

3. Optical devices

Igor Aharonovich[1]
[1] School of Mathematical and Physical Sciences, University of Technology Sydney

Abstract text: Engineering robust, solid-state quantum systems is amongst the most pressing challenges to realise scalable quantum photonic circuitry. In recent years, quantum emitters in hexagonal boron nitride (hBN) have emerged as fascinating candidates for realisation of room temperature quantum technologies with hBN.

In this presentation I will discuss the photophysical properties of quantum emitters in hBN and expand on their utility in scalable quantum technologies. I will focus on avenues to engineer these defects and describe their most promising properties – including their spin – photon interfaces. Integration of the emitters with photonic resonators is in the heart of achieving quantum circuitry on chip, and I will present our most recent attempts to achieve this goal. Taking advantage of the unique 2D nature of hBN, I will also show potential assembly of quantum optoelectronic devices and discuss potential on chip tunability of quantum emitters in hBN.

All in all, hBN possesses all the vital constituents to become the leading platform for integrated quantum photonics. To this extent, I will highlight the challenges and opportunities in engineering hBN quantum photonic devices and will frame it more broadly in the growing interest with 2D materials nanophotonics.

Radio Frequency Devices 1 (Mobile Communication)

2025-07-07
11:00 - 12:15
Radio Frequency Devices 1 (Mobile Communication)

ED-Mon-1 - RF GaN-on-Si for Future 5G/6G Communications

4. Electronic devices

Geok Ing Ng[1]
Yuan Gao[1], Hanchao Li[2], Yihao Zhuang[3], Siyu Liu[3], Hanlin Xie[1], Qingyun Xie[1], Wee Leng Ong[1], Zhan Jiang Quek[1], Haorui Luo[1], Kumud Ranjan[1], Yi Heng Leong[1], Hsien-Shun Wu[1], Navab Singh[1], Surasit Chungpaiboonpatana[1]
[1] National GaN Technology Centre (NGTC), Agency for Science, Technology and Research (A*STAR), Singapore
[2] School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore
[3] Energy Research Institute, Nanyang Technological University, Singapore

Abstract text: As the growth of ubiquitous wireless connectivity in the 5G/6G era increases, there is a strong desire for high performance and cost-effective technology which could complement existing CMOS-based RF front end modules. This demand has spurred the strong interests in both academic R&D and major semiconductor companies in RF GaN-on-Si technology in recent years. As a result, excellent progress in GaN-on-Si devices has been made with performance closing to the more matured GaN-on-SiC counterparts.

The first part of this talk will present the recently reported RF GaN-on-Si HEMTs results from academic research at Nanyang Technological University (NTU) and industry. Notable results include competitive low-voltage (<5V) power and noise performance at mm-wave (Ka band), and the first demonstration of power amplification in D-band (123 GHz). These results demonstrate the tremendous potential of RF GaN-on-Si technology for future low-cost and high-performance 5G/6G communication applications. Fundamental research such as trap analysis will be discussed.

The second part of the talk will highlight how research institutes play an indispensable role in the lab to fab of RF GaN-on-Si, citing the case study of National GaN Technology Centre (NGTC), Singapore, which was launched in 2023 with an initial USD 85M investment. In addition to state-of-the-art industry-oriented R&D, the Centre will offer rapid prototyping service of high performance 8” GaN-on-Si CMOS-compatible process and 6” GaN-on-SiC process (qualified MMIC processes with PDKs). In addition to industry-grade fabrication equipment, the Centre hosts a wide suite of characterization facilities for advanced RF and reliability testing.

This work is sponsored in part by NRF and A*STAR under Grant No. M23WSNG001 and M22L3a0112.

ED-Mon-2* - High-Performance Ka-band AlN/GaN MIS-HEMTs with Ultra-Low Noise Characteristics for Next-Generation Communication Systems

4. Electronic devices

Hanchao Li[1]
Hanlin Xie[2], Zhongzhiguang Lu[1], Yihao Zhuang[3], Qingyun Xie[2], **Siyu Liu**[3], Geok Ing Ng[2]
[1] School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore
[2] National GaN Technology Centre (NGTC), Agency for Science, Technology and Research (A*STAR), Singapore
[3] Energy Research Institute, Nanyang Technological University, 1 CleanTech Loop, #06-04, Singapore

Abstract text: The growing demand for Ka-band (26.5-40 GHz) applications has intensified the need for Low Noise Amplifiers (LNAs) that simultaneously deliver good noise performance and power handling capabilities. While conventional InP and GaAs-based HEMTs offer superior noise characteristics, their limitations in power handling at receiver front-ends remain a critical drawback [1-3]. Although GaN HEMTs have established dominance in power applications, their potential for low-noise operation in Ka-band remains under explored.

This work demonstrates a significant advancement in Ka-band low-noise devices through AlN/GaN MIS-HEMTs. The optimized epitaxial structure with a 4 nm in-situ SiN cap layer and 5nm AlN barrier layer features a reduced gate-to-channel distance of 9 nm, which is 1.5× and 4× thinner than conventional InAlN/GaN and AlGaN/GaN structures, respectively. The devices with 120 nm gate length exhibit RF performance with a f_T of 124 GHz, $f_{max,Gu}$ of 150 GHz and $f_{max,\,MAG}$ of 178 GHz at V_{ds} of 5 V. The devices also demonstrate NF_{min} of 0.98 dB at 30 GHz, while maintaining high gain (G_a>10 dB) across the frequency range (10 to 32 GHz). The measured noise characteristics align closely with our simulation model and follow $NF_{min} = 1 + 2\omega C_{gs}/g_m \times [(R_g + R_s)/R_i]^{1/2}$[4], where the enhanced g_m/C_{gs} ratio through the heterostructure engineering and minimized parasitic resistances play important roles. The measured equivalent noise resistance R_n and normalized $R_n/|Z_{opt}|$ demonstrate promising characteristics for broadband LNA design. Notably, our devices achieve competitive noise performance compared to previously reported GaN HEMTs despite having a relatively large gate length.

In summary, our results demonstrate the feasibility of GaN-based low-noise devices for Ka-band applications. Further optimization through barrier layer engineering and surface treatment could potentially reduce $R_n/|Z_{opt}|$, enabling more robust noise performance and simplified matching network design. This work opens new possibilities for integrating high-power handling capability with excellent noise performance in next-generation communication systems.

[1] C. Sanabria et al., IEEE Electron Device Lett., 2006. [2] G. Gao, et al., IEEE Microw. Wireless Tech. Lett.,2024. [3] S. D. Nsele et al., IEEE Trans. Microwave Theory Techn., 2023. [4] P. Ladbrooke. "MMIC design: GaAs FETS and HEMTs.", 1989.

ED-Mon-3 - Ultra low RF losses of 0.14 dB/mm at 30 GHz on GaN on silicon wafers

4. Electronic devices

Matthew Charles[1]
Julien Delprato[1], Yveline Gobil[1], Fanny Morisot[1], Alex Chaumont[1], Matthieu Lafossas[1], Simona Torrengo[1], Mrad Mrad[2], Olivier Féron[2], Richard Weichelt[2], Christof Mauder[2], Dirk Fahle[2], Nicolas Muesgens[2], Erwan Morvan[1]
[1] Univ. Grenoble Alpes, CEA, LETI, 38000 Grenoble, France
[2] AIXTRON SE, Dornkaulstr. 2, 52134 Herzogenrath, Germany

Abstract text: Production of GaN-based RF devices typically depends on growth of GaN on semi-insulating SiC substrates, with high thermal conductivity and very low electrical conductivity. This is a costly material, only available up to 200mm diameter, and so it would be favourable to replace SiC with silicon, which is available as wafers 300mm in diameter, suitable for high precision CMOS-compatible fabs. There are many challenges to using high resistivity silicon wafers, in particular very low doping of ~10^{12}cm^{-3} and the fact that Ga and Al act as dopants in this material. Also, GaN growth temperature in metal-organic vapour phase epitaxy (MOVPE) is around 1000°C, which can cause these elements to diffuse into the silicon, further reducing its resistivity. This reduced resistivity causes losses in the RF devices, degrading their performance.

In this work, growth recipes and cleaning procedures were optimised to reduce RF losses, using an automated 1 x 300mm AIXTRON close-coupled showerhead (CCS) MOVPE tool, with in-situ Cl_2 based cleaning. RF losses were measured at 30GHz on 50-ohm coplanar waveguides 56µm wide.

Work in the literature shows that the AlN buffer layer and its nucleation should be optimised to limit Al diffusion into the silicon. The thermal budget should also be minimized. These two steps were implemented, and by altering the temperature uniformity on wafer, the uniformity of RF losses was optimized. However, this was not sufficient to reduce the losses reproducibly to very low values. Ga and Al concentrations in the silicon at the centre and edge were measured on 3 different wafers by SIMS. This showed that Al was not a significant factor in the wafer-to-wafer variation, but a direct correlation was shown between the concentration of Ga in the silicon and RF losses.

Following this, the chamber cleaning before wafer growth was further optimized to minimize the Ga left in the chamber, as this metal could diffuse into the silicon wafers before growth and lead to such doping. As a result, it was possible to repeatably achieve extremely low RF losses across the wafer, with a median value of 0.14dB/mm and a maximum of 0.15dB/mm. This demonstrates the capability of fabricating GaN on silicon wafers with extremely low losses, competitive with GaN on SiC wafers, while their large diameter gives access to high performance and efficient transistor processing.

ED-Mon-4 * - Au-Free 3D-Heterogeneous Integration of mmWave GaN-on-Si Dielets with Si CMOS and Glass Interposer for 5G NR FR2 Amplifiers

4. Electronic devices

Pradyot Yadav[1]
Xingchen Li[2], Jinchen Wang[1], Danish Baig[2], Juan Pastrana-Gonzales[3], John Niroula[1], Patrick Darmawi-Iskandar[1], Jan Strate[4], Cesar Neve[4], Ulrich Rohde[5], Ahmad Islam[3], Muhannad Bakir[2], Madhavan Swaminathan[6], Ruonan Han[1], Tomás Palacios[1]
[1] Microsystems Technology Laboratories, Massachusetts Institute of Technology, Cambridge, USA
[2] School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, USA
[3] Air Force Research Laboratory Wright-Patterson AFB, Dayton, USA
[4] Soitec, Hasselt, Belgium
[5] Federal University of the Armed Forces of Germany, Munich, Germany
[6] Department of Electrical Engineering, Pennsylvania State University, USA

Abstract text: GaN power amplifiers (PA) have set the benchmark for saturated power at high frequencies [1]. But, most GaN monolithic microwave integrated circuit (MMIC) processes are limited by available back-end-of-line (BEOL) layers, small wafer size, and a lack of digital circuit design options. On the other hand, Si CMOS benefits from an advanced BEOL at 300 mm wafer size with superior switch/digital/memory front-end-of-line (FEOL). To advance GaN circuit technology, 3D-heterogeneous integration (3DHI) advanced packaging technologies are required for the buildup of 3D-integrated circuits (3DIC) that leverage GaN / Si CMOS [2], in addition to multi-chiplet interposers for bringing several technology nodes to a single chip. In this work, we integrate GaN dielets with Intel 16 Si CMOS and glass interposers for 2.5D and 3D-stacking. Au-free AlGaN/GaN-on-Si HEMTs are fabricated with L_{SD} = 0.4 µm, featuring regrown contacts and a copper-based T-gate with -$L_{G(foot)}/L_{G(head)}$ = 0.08/0.81 µm. An Innolas LINEXO femtosecond laser singulates the dielets to a size of 240 µm 410 µm. The dielets are integrated with Intel 16 Si CMOS using thermocompressive Cu-Cu bonding. Two differential 3D-mmWave integrated circuit (3D-mmWIC) amplifiers are fabricated, one featuring neutralization capacitance, one without. The amplifier without neutralization capacitance, displays a peak gain of 4.8 dB with a 3 dB bandwidth of 26 – 30 GHz. The amplifier featuring neutralization capacitance displays a peak gain of 6.2 dB with a 3 dB bandwidth of 26 – 32 GHz. The large signal performance of these amplifiers was hindered by sub-optimal passivation of the GaN transistors.

In addition to the 3D-mmWIC technology based on GaN-CMOS integration, GaN dielets are also integrated into a glass substrate for device-in-package 2.5D circuit buildup. A 2-layer redistribution layer (RDL) is fabricated using semi-additive patterning (SAP) metal layers and low loss ABF (Ajinomoto Build-up Film). A single stage, single ended amplifier featuring T-line matching is fabricated with a 3 dB bandwidth of 27.4 - 34.6 GHz and peak gain of 7.5 dB.

This work was funded in part by the NDSEG Fellowship and CHIMES, one of the Seven Centers in JUMP 2.0, a Semiconductor Research Corporation (SRC) Program.

[1] H. Wang et al., *ETH PA Survey*, 2024. [2] H. W. Then et al., *MWTL* 33(6), 2023.

VCSELs

2025-07-07
11:00 - 12:15
VCSELs

OD-Mon-1 - Addressable 2D Array of GaN-based VCSELs with Curved Mirrors

3. Optical devices

Kentaro Hayashi[1]
Yukio Hoshina[1], Tatsuro Jyokawa[1], Yuichiro Kikuchi[1], Yuki Nakamura[1], Maho Ohara[1], Tomohiro Makino[1], Hiroyuki Miyahara[1], Takumi Watanabe[1], Koji Yoneda[1], Miwako Shoji[1], Masahiro Murayama[1], Eiji Nakayama[1], Tatsushi Hamaguchi[2], Rintaro Koda[1], Noriyuki Futagawa[1]
[1] Sony Semiconductor Solutions Corporations, Asahi 4-14-1, Atsugi 243-0014, Japan
[2] present affiliation: Mie university

Abstract text: GaN-based vertical-cavity surface-emitting lasers (GaN-VCSELs) are expected to be applied to various light sources, such as displays, lighting, and laser headlamps. Arraying and individual driving of these VCSELs will enable further attractive applications. Particularly for lighting applications, in an arrayed light source, selective illumination of specific regions allows for the irradiation of only the corresponding target areas. This approach effectively minimizes unnecessary illumination of non-target regions and contributes to a reduction in power consumption. Our research group has developed GaN-based VCSELs with curved mirror, achieving an emission divergence of less than 4 degrees, which enables more uniform and precise illumination performance. The lower emission divergence of GaN-VCSELs compared to edge-emitting lasers (over 10 degrees) contributes to reduced optical crosstalk in two-dimensional arrays. This presentation reports on the research results regarding the independent driving of a two-dimensional array of GaN-based VCSELs with curved mirror.
The fabricated GaN-based VCSEL array in this study consists of a 7×7 square matrix structure (73 μm pitch) containing 49 single elements. To achieve individual driving of each element, a passive matrix structure was employed. In this structure, only the device located at the intersection of the anode and cathode to which a voltage is applied is activated and illuminated. To prevent electrical crosstalk between adjacent elements, isolation of the p-type GaN and n-type GaN layers was required. The p-type GaN layer was isolated by boron ion implantation, while the n-type GaN layer was isolated by stacking a semi-insulating GaN layer, followed by mesa formation through dry etching.

The GaN-based VCSEL array with a curved mirror and passive matrix structure successfully demonstrated independent driving of individually addressed elements. Independent driving was achieved for all 49 elements in the 7×7 array, with a representative element exhibiting a threshold current of 2.9 mA and CW operation at room temperature. The emission peak wavelength was 444 nm. To the best of the authors' knowledge, this is the first demonstration of independent driving in a GaN-VCSEL array, representing a pioneering achievement in this field.

OD-Mon-2* - In-plane distribution and high wall-plug efficiency of GaN-based vertical-cavity surface-emitting lasers

3. Optical devices

Naoki Shibahara[1]
Taichi Nishikawa,[1], Ruka Watanabe[1], Mitsuki Yanagawa[1], Shoki Arakawa[1], Atsunori Tokushi[1], Taiki Kitamura[1], Satoshi Kamiyama[1], Motoaki Iwaya[1], Tetsuya Takeuchi[1]
[1] Meijo University

Abstract text: We developed an accurate control (± 0.3%) of the cavity length in GaN-based vertical-cavity surface-emitting lasers (VCSELs) by in-situ reflectivity spectra measurement.[1] We then reported a wall-plug efficiency of 21.3% under continuous wave operation at room temperature (RT).[2] On the other hand, when an in-plane thickness distribution exists across the wafer, these could cause variations in the laser characteristics. In this study, we measured in-plane distributions of a DBR center wavelength (WL), a resonance WL, and a spontaneous peak WL of the VCSELs across the wafer and investigated their influences on the laser characteristics.

The VCSEL structure in this study consisted of a bottom 40-pair AlInN/GaN DBR, and a 4λ cavity with a GaInN active layer fabricated on a GaN substrate (a quarter of 2 inch). The cavity length was controlled by the in-situ measurement which monitored a point of 17 mm away from the 2 inch wafer center. We measured in-plane distribution of the three WLs from 17 mm to the wafer center. The DBR center WL was measured with ex-situ reflectivity measurement. As the resonance WL, the lasing WL was measured from the VCSEL structure. The spontaneous peak WL was measured from a VCSEL-like structure without the top DBR fabricated simultaneously with the VCSEL structure.

The DBR center WL and the spontaneous peak WL were uniform across the wafer from 17 mm to 5 mm (from the wafer center), showing 416 nm ± 1 nm and 411 nm ± 1.5 nm, respectively. In contrast, the resonance WL was redshifted by 5 nm from 417 nm (17 mm) to 422 nm (5 mm). We then observed in-plane nonuniformity of differential EQE of the VCSELs from 50% (17 mm) through 70% (10 mm) to 60% (5 mm). We found in-plane nonuniformity of the threshold current density from 7.8 kA/cm² (17 mm) to 14.3 kA/cm² (5 mm). Based on the above results, the in-plane nonuniformity of the laser characteristics was caused by that of the resonance WL.

Finally, we obtained even better VCSEL characteristics than previously reported.[2] A differential EQE, a threshold current density, the maximum light output power (LOP), and the maximum WPE of the VCSELs were 65.7%, 7.3 kA/cm^2, 16.2 mW, and 27.6%, respectively.

[1] T. Nagasawa, et al., Jpn. J. Appl. Phys. 62, 066504 (2023).

[2] R. Watanabe, et al., Appl. Phys. Lett. 124, 131107 (2024).

OD-Mon-3* - Design of Single-Mode and Polarization stable 450 nm Vertical Cavity Surface Emitting Laser (VCSEL) with Surface Relief and Sub-Wavelength Grating

3. Optical devices

Lakshminarayan Sharma[1]
Lars Persson[1], Joachim Ciers[1], Åsa Haglund[1]
[1] Chalmers University of Technology, Department of Microtechnology and Nanoscience, 41296 Gothenburg, Sweden

Abstract text: Blue single mode VCSELs are at an early stage of development. They have been obtained by either reducing the size of the waveguide, which results in a high device resistance, or using an extended cavity with curved DBRs, which often results in multiple longitudinal modes or mode hopping. An alternative approach is a shallow localized surface relief etched into the top layer of a DBR. Such a structure transversely tailors the mirror reflectivity providing high reflectance for the fundamental mode and lower reflectivity for higher order modes with larger overlap with the periphery of the aperture. By incorporating a sub-wavelength grating, polarization pinning can also be achieved through the difference in effective refractive index for the two linear polarization states.

We here employ the 2D effective index method (EIM) to investigate designs for single-transverse mode and polarization stable blue VCSELs. The starting point is a 10-λ cavity VCSEL with all-dielectric Distributed Bragg Reflector (DBRs) of SiO_2/Nb_2O_5 and a 6-μm SiO_2 aperture. The modal and polarization discrimination are investigated as a function of surface relief diameters between 1.5 μm to 5.5 μm and as a function of outcoupling DBR pairs between 8 and 10 with a highly reflective 11-pair DBR. A reasonable modal discrimination in threshold gain of ~150 cm^{-1} requires etching into the outcoupling DBR to a λ/4-depth for an 8-pair DBR, a 3λ/4-depth for a 9-pair DBR and a 5λ/4-depth for a 10-pair DBR. An optimal relief diameter of 3.5 μm maximizes the modal discrimination and favors operation in the fundamental LP_{01} mode. For relief diameters smaller than 2.0 μm the losses for the LP_{02} mode become lower than that of LP_{01}, and for too large diameters the modes experiences too similar mirror reflectivity. To ensure polarization-stable performance a sub-wavelength grating is included in the 3.5-μm diameter surface relief. For a 70% duty cycle (ridge to period ratio) a high modal and polarization discrimination of 150 cm^{-1} can be obtained for a very wide etch depth range between 50-100 nm. This is a very large etch depth tolerance compared to similar designs for infrared VCSELs and is due to the low refractive index of SiO_2 in the DBR. This design provides a pathway to reproducible single-mode and polarization stable blue VCSELs without negatively affecting other laser performance.

OD-Mon-4* - Distributed Bragg reflectors with porous GaN: Reconsidering the effective medium approximations

3. Optical devices

Frederik Lüßmann[1]
Matthias Hoormann[1], Jana Hartmann[1], Florian Meierhofer[1], Andreas Waag[1]
[1] Institute of Semiconductor Technology, Technische Universität Braunschweig, Braunschweig, Germany

Abstract text: In recent years, electrochemical porosification of GaN has emerged as a competitive alternative to MOVPE growth for constructing low-refractive index layers in nitride-based optical device structures. Key applications, such as VCSELs and edge-emitting lasers, have been demonstrated incorporating porous GaN layers. While the development of these optical components has continuously advanced, the investigation of fundamental properties of porous GaN lags behind with respect to these devices.

The behaviour of porous GaN distributed Bragg reflectors (DBRs) mainly relies on the tunable refractive index of the porous GaN layers. The lowering of its refractive index is a direct consequence of an increase in its porosity. The relationship between these two observables is typically described by employing an effective medium approximation. From the multitude of suitable approaches, the volume averaging theory (VAT) has been predicted by [1] to yield the most accurate results, according to numerical simulations. Based on this result, the nitride community has commonly adopted the VAT to describe the porosity-dependent refractive index in porous GaN DBRs [2-5]. Most data on porosity presented in publications are derived from the refractive index utilizing the VAT. This is largely due to the fact that whilst the refractive index can be readily assessed through optical measurements, accurately determining porosity is much more complex.

In this contribution, we present independent measurements of both index of refraction and porosity, allowing to test the VAT model. We show that the necessary conditions presented in [1] for applying VAT are not necessarily met for DBR layers as thin as 50 nm and that a different effective medium approximation describes the obtained data significantly more accurate.

References:

[1] M. M. Braun *et al*., *Thin Solid Films*, **496**, 505 (2006).
[2] C. Zhang *et al*., *ACS Photonics*, **2**, 980 (2015).
[3] Y. Tian *et al*., *Materials*, **15**, 3536 (2022).
[4] M. Sawicka *et al*., *Mater. Sci. Semicond. Process*, **155**, 107234 (2023).
[5] N. C. Palmquist *et al*., *Photonics*, **10**, 646 (2023).

Industrial Session

2025-07-07
11:00 - 12:20
Industrial Session

IN-1 - On The Current State of PVT-AlN Commercial Production

1. Growth

Gregory Mills[1]
[1] HexaTech, Inc. 991 Aviation Parkway Suite 800 Morrisville, NC 27560

Abstract text: HexaTech will present the state-of-the-art in commercial production of bulk, PVT-grown single crystal aluminum nitride (AlN). Highlighted will be current material characteristics of 2-inch diameter material, including bulk and surface quality, substrate shape, and deep-UV transparency performance. Also discussed will be HexaTech's diameter expansion activity towards commercial 100 mm product, tied to the recently launched DARPA UWBGS program. Further presented will be HexaTech's latest product launch, an optimized, standard N-face product, and related characteristic data. Last will be a short discussion on recent capacity expansion across the production process, supporting larger diameter material.

IN-2 - Centralized Bulk Precursor Delivery by Means of Direct Liquid Injection

1. Growth
Ehsan Mohseni[1]
Johannes Grübler[1], Jörg Koch[1]
[1] SEMPA SYSTEMS GmbH

Abstract text: Deposition techniques such as chemical vapor deposition (CVD) and atomic layer deposition (ALD) are particularly suitable for the deposition of specific elements delivered by precursor chemicals. They achieve industrial standards for film thickness, uniformity, and purity for coatings much more reliably than physical deposition and wet chemical techniques. Both techniques, which are used in the semiconductor, photovoltaic and optoelectronic industries, among others, require a precise and reliable supply system of precursor materials, which poses several difficulties. Only 10% of industrially available precursors are gaseous, while about 80% are in the form of powders or crystals. Solid precursors are the most challenging among others because the sublimation rate is directly related to the free surface area, which changes as sublimation progresses, resulting in a non-constant mass transport rate during the deposition. In addition, most of the available precursors have safety requirements.

Non-gaseous precursors are commonly delivered by evaporation. This is conventionally realized using bubbler or vapor draw technologies, where a carrier gas passes through or by the precursor. The vapor delivery rate depends on the temperature, pressure, and in case of the bubbler, the carrier gas flow. Increasing the latter may lead to temperature instability and fluctuations in delivery rate. Because of this thermodynamic limitation, the use of bubblers is recommended when low precursor consumption is required, and typically each deposition reactor requires its own bubbler.

Direct liquid injection (DLI) is an alternative vapor delivery technology in which the precursor is directly vaporized and injected into the reactor. Unlike bubbler technology, the supply rate in DLI is not limited by the vapor pressure. This makes it particularly interesting for precursors with low thermal stability and low vapor pressure. Fully automated with high-precision flow and pressure controllers, DLI allows high-throughput precursor supply while maintaining an adjustable concentration range both below and above atmospheric pressure level. This allows one DLI system to be used as a central supply unit for multiple reactor chambers, resulting in a compact design and reduced footprint. Here we present our latest DLI technology designed for liquid as well as solid precursors.

IN-3 - Innovation in GaN

1. Growth
Christian Geng[1]
[1] AIXTRON SE, Dornkaulstr. 2, 52134 Herzogenrath, Germany

Abstract text: Innovation is essential for success in advanced technologies. Every player in the high-tech field needs an Innovation Strategy to compete with and outperform its peers.

For equipment manufacturers, days of simply providing hardware are over. AIXTRON provides solutions for the customers' applications – from R&D to device production. For one, this enables the end-user to have a quick start and a fast return of investment. But getting the feedback by running the tools in the same mode as the end-user is invaluable: it is vital when tuning the equipment for endurance, throughput and uptime. It is the way to understand scheduled and unscheduled maintenance / downtime and to optimize such.

Shopfloor and Laboratory are essential test grounds. AIXTRON tops this with an Innovation Center of 1000m^2 clean room. In focus is research and development of 300mm tools and epitaxial processes.

In a multitude of collaborations and funded research projects with renowned partners, we demonstrate how to push the limits of physics by developing increasingly thick GaN HEMT stacks on Si substrate to achieve Breakdown Voltages well beyond 1200V at 1µA/mm^2.

For the application of Power Management and RF devices, AIXTRON demonstrates its successful strategy by being the clear market leader in a rapidly growing market. Successive products for 150mm, 200mm and 300mm wafers with increasing productivity and successively reduced Cost of Ownership secure AIXTRON's market position and the productivity of device manufacturers – the ultimate "win / win".

IN-4 - Advancing Gallium Nitride Research: ProNano's Role in Academic & Industrial Innovation

1. Growth
Ashutosh Kumar[1]
Linda Johansson[1], Peter Ramvall[1]
[1] RISE Research Institutes of Sweden, Ole Römers väg 1 Lund 22363, Sweden

Abstract text: The RISE ProNano is a pioneering environment focused on the industrialization of semiconductor-based materials, processes, and components. Established in 2020, ProNano represents Sweden's first innovation hub for scaling up innovations, providing both startups and established companies with access to advanced infrastructure without the need for substantial capital investment. ProNano helps in building an ecosystem by offering a platform for Swedish deep-tech start-ups and SMEs in semiconductors and nanotechnology to connect and collaborate locally. The facility spans 3,400 m² and includes a 210 m² ISO 5 cleanroom, 180 m² of chemical and biological laboratories. It is equipped with state-of-the-art tools, such as the advanced AIXTRON Metal-Organic Chemical Vapor Deposition (MOCVD) high-temperature reactor and a cutting-edge Hitachi Scanning Electron Microscope (SEM) with Energy Dispersive Spectroscopy (EDS) and Scanning Transmission Electron Microscopy (STEM) capabilities. These instruments support the production and analysis of nanowires and nanostructures, which are crucial for the development of next-generation energy and lighting systems.[1]

In this presentation, I will discuss the pivotal role of ProNano in supporting Swedish startups such as Hexagem and Polar Light Technologies, both of which specialize in developing energy-efficient Gallium Nitride (GaN) semiconductors for lighting applications. By leveraging ProNano's MOCVD reactor, SEM facilities, and expert competencies, these companies have made significant advancements in their technology, with the goal of attracting industrial partners and scaling up their production. Additionally, I will highlight how ProNano has played a key role in supporting AlixLabs, a company utilizing RISE's cleanroom facilities to develop its innovative Atomic Layer Pitch Splitting technology. To conclude, I will discuss ProNano's involvement in the development of GaN-based vertical transistors under the All2GaN project, which is part of the Chips JU initiative.[2] This project, jointly funded by Vinnova, has RISE as the national coordinator and represents another example of ProNano's contribution to advancing cutting-edge semiconductor technologies.

1. https://www.ri.se/en/test-demo/pronano-scale-up-your-innovation-with-nano-and-gan-materials
2. https://www.ri.se/en/expertise-areas/projects/all2gan-affordable-smart-gan-ic-solutions-for-greener-applications

IN-5 - Recent development of QUANFine with back barrier

1. Growth

Anders Lundskog[1]
Ding Yuan Chen[1], Ben Hammou[2], Francois Grandpierron[2], Elodie Carneiro[2], Katir Ziouche[2], Etienne Okada[2], Jr-Tai Chen[1], Farid Medjdoub[2]
[1] SweGaN AB, 58330 Linköping, Sweden
[2] CNRS-IEMN, Institut d'Electronique, de Microélectronique et de Nanotechnologie, Villeneuve d'Ascq, France

Abstract text: QuanFINE buffer-free GaN-on-SiC HEMTs offer a promising platform for high-frequency, high-power RF applications, enabling ultrathin epitaxy, strong confinement, and efficient heat dissipation, key for aggressive scaling. This approach allows the AlN-nucleation layer to act as a back-barrier, limiting short channel effects and removing buffer leakage. Yet, despite removing the traditional doped buffer, downscaled QuanFINE HEMTs still suffer from trapping effects that degrade performance.

We present a modified QuanFINE architecture that mitigates trapping while maintaining excellent confinement and boosting power performance. Three AlGaN/GaN HEMTs using QuanFINE are studied. All feature AlN nucleation, GaN channel, and AlGaN (50% Al) barrier, and hybrid passivation (GaN cap + LPCVD SiN). Pulsed I-V reveals significantly reduced current collapse, especially at high VDSQ, that stems either from the increased 2DEG to GaN/AlN interface distance (a known trapping site) or from the BB screening.

CW Load-pull at 40 GHz (VDS=20V) demonstrate superior performance for the wafer with BB, achieving both higher PAE (47% vs. 39%) and increased Pout (2.30 W/mm vs. 1.55 W/mm) as compared to the wafer without BB.

IN-6 - Enabling Next-Generation Devices with Ultra-High-Quality AlN and AlGaN Epitaxy

1. Growth

Ronny Kirste[1]
[1] Adroit Materials Inc., Cary, NC, USA

Abstract text: Adroit Materials develops epitaxial thin films of aluminum nitride (AlN), aluminum gallium nitride (AlGaN), and GaN structures to support the most demanding applications in ultraviolet optoelectronics, high-power electronics, and emerging quantum technologies. By growing these materials directly on single-crystal AlN or GaN substrates, Adroit achieves dislocation densities as low as 10E3 cm-2 - several orders of magnitude lower than those obtained with conventional heteroepitaxy on sapphire, silicon carbide, or silicon. These improvements translate into measurable gains in device efficiency, yield, and long-term reliability, particularly in structures where thermal conductivity, breakdown strength, or interface stability are limiting factors.

Adroit's process capabilities include precise control over doping profiles in both AlN and AlGaN, enabling formation of functional n-type and p-type layers for UV-C LEDs, HEMTs, diodes, and other structures. The company offers customization of layer compositions, thicknesses, doping, and interfaces to meet specific customer device targets. The advantage for university and business users of Adroit's foundry service is that they can leverage decades of III-nitride materials and epitaxy experience to reduce the risks and delays commonly associated with developing new growth processes. By outsourcing complex epitaxial work to a partner focused on crystalline quality and process control, customers are free to focus their efforts on materials characterization, device design, and system-level performance. This collaborative model allows researchers and developers to accelerate their innovation cycles while working with production-grade material quality, even at low wafer volumes and with non-standard requirements. While epitaxy remains the core offering, Adroit supports select partners with device fabrication and eprototyping to accelerate materials-to-device validation.

This presentation will provide an overview of Adroit's epitaxial platform, highlight performance metrics from selected devices grown on low-defect AlN, and discuss how tight process-feedback cycles are enabling rapid innovation in wide bandgap device engineering.

IN-7 - Advancing GaN Metrology: Powerful Solutions for GaN Characterization

2. Physics and characterization

Zsolt Szekrényes[1]
Agnes Honti[1]
[1] Semilab Zrt.

Abstract text: The ever-growing need for electric power is a long-lasting problem for human society. In recent decades the semiconductor industry started to deviate from silicon and explore new materials that can achieve more efficient use of electric power. But with the proposition of these new wide bandgap materials (like SiC & GaN) new challenges arose. Semilab has an extensive metrology line-up of optical and electrical systems for characterization of GaN semiconductor materials. Photoluminescence is a powerful method to identify key characteristics of important parameters of AlGaN layers, while ellipsometry is a must to examine key features of the thin layers of the GaN HEMT stack. Semilab has tackled these challenges and can offer solutions with SPL (spectral photoluminescence) and uSE (micro-spot spectroscopic ellipsometry) product lines, enabling the quality manufacturing of 3rd generation semiconductor devices.

IN-8 - Atomic Layer Etching for next generation semiconductor devices

1. Growth

Reza Jafari Jam[1]
Robin Atle[1], Amin Karimi[1], Yoana Ilarionova[1], Asif Muhammad[1], Intu Sharma[1], Fred Roozeboom[2], Jonas Sundqvist[1], Dmitry Suyatin[1]
[1] AlixLabs AB, Ole Römers Väg 1, Entrance H, 223 63 Lund, Sweden
[2] Faculty of Science & Technology, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands

Abstract text: Atomic Layer Etching Pitch Splitting (APSTM)1,2,3 is an innovative and cost-efficient patterning method that offers an alternative to the conventional Self-Aligned Multi Patterning (SAMP) for creating sub-20-nm features. By integrating atomic-scale processes such as Atomic Layer Etching (ALE) with established manufacturing techniques, APS enables selective material removal without the numerous deposition and etching steps needed in SAMP. This streamlined
approach delivers high precision and patterning accuracy, essential for defining critical device structures.

APS is a highly repeatable process with strong potential for high yield and outstanding resolution—key requirements for next-generation semiconductor technology. Our estimates suggest that APS could lower wafer manufacturing costs by up to 40% per mask layer while also boosting throughput. Additionally, by using fewer process gases and eliminating multiple fabrication steps, APS supports industry objectives for reducing resource usage and cutting CO_2 emissions.

In addition to the APS process, we have developed various ALE processes tailored for specific applications, including power electronics. Our work includes demonstrating surface smoothening on materials such as SiC, GaN, and AlGaN, as well as achieving controlled etching of GaN to enable soft-landing on underlying AlGaN layers. Beyond these materials, we have also developed ALE processes for Si, SiO_2, SiN_x, TiN, and GaP, with ongoing research and development focused on expanding this portfolio to include several additional materials.

References:
1. US Patent 10,930,515, Feb. 23, 2021.
2. US Patent 11,424,130, Aug. 23, 2022.
3. J. Sundqvist et al., SPIE 2025, paper 13429-28.

Acknowledgments
We would like to acknowledge support from the Ascent+ European Union's Horizon 2020 research and innovation program and Vinnova for financing this work under grants GA No 871130 and No. 2024-00586, respectively.

Boron Nitride crystals and applications

2025-07-07
11:00 - 12:15
Boron Nitride crystals and applications

GR-Mon-B1 - Bulk Crystal Growth of Hexagonal Boron Nitride from Molten Metal Solutions

1. Growth

James Edgar[1]
[1] Kansas State University, Tim Taylor Department of Chemical Engineering, Manhattan, KS 66506 USA

Abstract text: The structural, electronic, and optical properties of hexagonal boron nitride (hBN) are unique among the two-dimensional materials. In contrast to graphite, it is an electrical insulator with an ultrawide energy band gap (~6 eV). Point defects in hBN can be single photon emitters. Its infrared optical properties are hyperbolic, with both negative and positive permittivities in different crystallographic directions. The boron-10 isotope has one of the largest thermal neutron cross-sections in the periodic table. These properties make hBN an excellent candidate for many solid-state devices including resistive random-access memories (RRAM), ultraviolet and visible light emitters, nanophotonics, molecular spectroscopy, neutron detectors, and quantum sensors. To achieve their best performance and highest efficiency, all of these devices require hBN with a low density of residual defects and impurities.

hBN synthesis and crystal growth from molten metal solutions meets these requirements. The process take place at atmospheric pressure and high temperature (1550 °C). Solvents are selected from metals with a high solubility for boron (Ni, Fe, and Co) and nitrogen (chromium). Elemental boron, boron nitride, and molecular nitrogen are the sources. The properties of these hBN crystals are excellent as verified by narrow Raman peak widths, high photoluminescence intensity energies greater than 5.7 eV, and low background concentrations of carbon and oxygen.

hBN crystals enriched in boron-10, boron-11, and nitrogen-15 isotopes have been grown and analyzed. Because of its longer hyperbolic polariton lifetime, $h^{10}BN$ is superior to hBN (with the natural distribution of boron isotopes) for nanophotonics. The remote interfacial photon scattering noise in graphene transistors is lower when encapsulated with hBN with a single boron isotope (either $h^{10}BN$ or $h^{11}BN$). Magnetic field sensing by spin defects is improved with $h^{10}B^{15}N$ due to the lower nuclear spin of ^{15}N compared to ^{14}N.

Scaling hBN crystal growth to produce large crystals is expected to greatly expand its applications, including as substrates for the epitaxial growth of a wide range of 2D and 3D materials. They can also enable the integration of multiple devices on a single substrate. The challenges that must be addressed to realize this goal will be discussed.

GR-Mon-B2 - High-temperature MBE of hBN: single-photon emitters, lateral heterostructures and use of isotopically enriched boron.

1. Growth

Tin S. Cheng[1]
Jonathan Bradford[1], Christopher J. Mellor[1], Kenji Watanabe[2], Takashi Taniguchi[2], Igor Aharonovich[3], Luiz F. Zagonel[4], Brenard Gil[5], James H. Edgar[6], Guillaume Cassabois[5], Peter H. Beton[1], **Sergei V. Novikov**[1]
[1] School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK
[2] National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan
[3] School of Mathematical and Physical Sciences, University of Technology, Sydney, Australia
[4] Institute of Physics, University of Campinas, UNICAMP, Campinas, 13083-859, Brazil
[5] Laboratoire Charles Coulomb, CNRS-Université de Montpellier, 34095, Montpellier, France
[6] Tim Taylor Department of Chemical Engineering, Kansas State University, Manhattan, KS 66506, USA

Abstract text: There has been a surge of interest in hexagonal boron nitride (hBN) due to its technological potential for deep ultraviolet (DUV) photonics, single photon emitters (SPEs) and through its incorporation into van der Waals (vdW) two-dimensional (2D) heterostructures.

We have developed high-temperature molecular beam epitaxy (HT-MBE) of hBN at growth temperatures from 1100ºC to 1700ºC using high-temperature sublimation and e-beam MBE sources for boron and nitrogen RF-plasma sources. We have demonstrated a direct optical energy gap of ~6.1 eV and electronic band gap of ~6.8 eV in single monolayer hBN.

We will demonstrate that the single-photon emitters in hBN layers can be reproducible grown by HT-MBE using carbon doping. To gain insight into the nature of carbon-related defects we have employed low-temperature scanning tunnelling microscopy/ spectroscopy.

Recent studies worldwide have focused on the development of novel 2D lateral heterostructures with unique transport and optical properties. Whereas vertical 2D heterostructures can be produced by epitaxy or by exfoliating and stacking of 2D layers, lateral 2D heterostructures can only feasibly be produced by an epitaxial growth process. Sequential HT-MBE growth of hBN, graphene and a second cycle of hBN growth resulted in the formation of lateral hBN–graphene–hBN heterostructures, in which a strip of graphene is laterally embedded between monolayers of hBN.

Boron has two naturally occurring stable isotopes, the natural mixture contains ^{11}B (80.1%) and ^{10}B (19.9%). We have studied HT-MBE of hBN using the boron source material with natural boron mixture and isotopically enriched (96%-98%) boron ^{10}B and boron ^{11}B with 5N and 6N purity. We demonstrated previously that during HT-MBE there is unintentional doping of the layers with boron due to decomposition of the pyrolytic boron nitride (PBN) parts of the nitrogen RF plasma sources. We will discuss the influence of the different MBE growth conditions on the resulting isotopic purity of hBN layers.

GR-Mon-B3 - Conditions for hBN crystallization at high N2 pressure

1. Growth
Stanisław Krukowski[1]
Bohdan Sadovyi[1], Petro Sadovyi[1], Sylwester Porowski[1], **Izabella Grzegory**[1]
[1] Institute of High Pressure Physics Polish Academy of Sciences Unipress, 01-142 Warsaw, Poland

Abstract text: Single crystals of hBN have been grown on the surface of Ni under pressure of N_2 gas of 1000-1500 bar (Fig.1-supp.). Due to increased solubility of N it was possible to grow hBN crystals significantly thicker than by similar approach but at atmospheric pressure.

The results of the experiments are discussed in the context of the thermodynamic properties of III-N compounds and the effect of the solvent on the thermal stability of BN with respect to its components.

To optimize the crystallization process, a key factor is to control supersaturation i.e. deviation of the growth system from thermodynamic equilibrium. The minimum N_2 pressure required for the stability of BN AlN, GaN and InN at high temperatures is very sensitive to the bonding energies in the crystals. The differences in the equilibrium N_2 pressure over III-N crystals could reach ten orders of magnitude(Fig. 2 supp.).

For pure condensed phases: BN and B, their activities are equal 1 by definition, so the equilibrium constant K of BN synthesis reaction is expressed just by . This equilibrium pressure (Fig.2b and Fig. 3b – supp.) can be increased by the reduction of the boron activity by its dissolution in Ni (or in another solvent), so that activity will deviate from unity. The pressure of N_2 gas necessary for stability of BN will be dependent on thermodynamic activity of B dissolved in Ni:

$$p_{N2}^{Ni} = p_{N2}^{eq}/a_B^2$$

A general tendency in the Ni-B system at the low boron concentration and at (1000–2000)K, is that the activity of boron is much less than its corresponding concentration, indicating large deviation of the solution from ideality where no solute-solvent interaction is assumed. It induces a strong shift of the BN equilibrium curve towards higher N_2 pressures. For 10at.% dilution of B in Ni, the shift is as high as 5-6 orders of magnitude (Fig. 3b supp.).

From above evaluations, it follows that at least, for a Ni solvent, the concentration of boron can be optimized to meet thermodynamic equilibrium for BN formation at 1 bar or even higher N_2 pressure. In this context the successful hBN growth at elevated N_2 pressure can be explained by slow kinetics of delivery of boron from B/BN solid source.

The discussion will be extended towards systems more suitable for hBN growth using high N_2 pressure to increase N solubility but also to be closer to thermodynamic equilibrium.

GR-Mon-B4 - The Detrimental Effect of Carbon on Epitaxial Boron Nitride Films

1. Growth

Henrik Pedersen[1]
Sachin Sharma[1], Hans Högberg[1]
[1] Linköping University

Abstract text: Boron nitride (BN) is a promising 2D material as well as a potential wide-bandgap semiconductor. Chemical vapor deposition (CVD) is commonly used to deposit single layers or thin films of BN, but the deposition process is insufficiently understood at an atomic scale and a CVD process that can be used to grow thicker epitaxial pristine h-BN has not yet been realized. We have studied CVD of sp^2-hybridised BN using the organoborons triethylboron (TEB) and trimethylboron (TMB) in combination with ammonia on sapphire substrates with the aim of better understanding the process at the atomic scale.

Using high resolution (scanning) transmission electron microscopy and electron energy loss spectroscopy, we can show that hexagonal-BN (h-BN) nucleates and grows epitaxially for about four nm before it either polytype transforms to rhombohedral-BN (r-BN), turns to less ordered turbostratic-BN or is terminated by a layer of amorphous carbon. We propose that the carbon in the organoborons deposits on the epitaxially growing h-BN surface and that this either leads to the polytype transition to r-BN, the transition to less ordered BN growth, or complete surface poisoning with carbon terminating BN growth. We also show that oxygen diffusion from Al_2O_3 substrates locally changes the AlN buffer, forming an AlON interlayer between AlN and BN. We suggest that the localized modifications made to the Al_2O_3 substrate and the AlN buffer during CVD influence the local polytype transition and epitaxial BN film morphology.

These results contribute to a more detailed understanding of the CVD process for BN and question the use of organoborons in CVD of epitaxial BN films, the polytype stability of h-BN growing on graphene, and the use of sapphire for growth of BN films.

Novel nitrides & deep UV

2025-07-07
11:00 - 12:15
Novel nitrides & deep UV

PC-Mon-1 - Nitride materials with unconventional structures and semiconducting properties

2. Physics and characterization

Andriy Zakutayev[1]
[1] National Renewable Energy Laboratory, Golden CO USA

Abstract text: Nitride materials with unconventional structures and semiconducting properties

Andriy Zakutayev

National Renewable Energy Laboratory

Nitride semiconductors such as GaN, AlN, InN have been traditionally confined to main-group elements and wurtzite crystal structures, where they made amazing technological advances in optoelectronic and power conversion applications. Recent discoveries of other unique properties upon alloying nitride semiconductors with transition metal nitrides that tend to form rocksalt structures, for example piezoelectricity and ferroelectricity in (Al,Sc)N, leads to a question: what other useful properties can be hiding in nitrides with other crystal structures?

In this presentation, I will give an overview of several novel nitride semiconductors with crystal structures beyond wurtzite, and discuss their physical properties and potential applications. The first example is $ZnTiN_2$ with wurtzite-derived structure and optical absorption onset under 2 eV, self-passivating surfaces, with potential application in photoelectrochemical CO_2 reduction [1,2]. The second example are layered nitrides, such as $MgMoN_2$ and $ScTaN_2$, with narrower band gaps and open-shell transition metal ions promising for thermoelectric and quantum applications [3,4]. The third example is Gd-containing nitride perovskites $GdWN_3$ and other structures that may be suitable for radiation detector applications due to high scatter crossection of Gd to neutrons. [5,6]

All these materials are synthesized at NREL by Physical Vapor Deposition methods such as sputtering, showing the proof of principle of their useful properties, and making them ripe for higher quality epitaxial growth and device integration by Molecular Beam Epitaxy or Metal-Organic Chemical Vapor Deposition. The application of advanced thin film deposition methods to nitrides semiconductors will be also discussed in this presentation.

[1] Journal of the American Chemical Society 144, 13673 (2024)

[2] Journal of Materials Chemistry A 12, 4544 (2024)

[3] Nature Synthesis 3, 1471 (2024)

[4] ACS Materials Letters 3, 1677 (2021)

[5] Applied Physics Letters 125, 112902 (2024)

[6] Chemistry of Materials 34, 10639 (2024)

PC-Mon-2* - Emission characteristics and carrier injection of far-UVC light emitting diodes with emission wavelength between 218 nm and 242 nm

2. Physics and characterization

Jakob Höpfner[1]
Tim Kolbe[2], Paula Vierck[1], Sylvia Hagedorn[2], Jens Rass[2], Hyun Kyong Cho[2], Tim Wernicke[1], Michael Kneissl[1], Sven Einfeldt[2], Markus Weyers[2]
[1] Technische Universität Berlin, Institute of Solid State Physics, Berlin, Germany
[2] Ferdinand-Braun-Institut (FBH), Gustav-Kirchhoff-Str. 4, Berlin, Germany

Abstract text: AlGaN-based far-ultraviolet-C (far-UVC) light-emitting diodes (LEDs) have been shown to be effective light sources for skin-safe disinfection, particularly in the eradication of multi-drug-resistant germs as well as for optical gas sensing (e.g. NO, NH_3).

In this paper, we analyse the electro-optical characteristics of far-UVC LEDs with emission wavelengths ranging from 218 nm to 242 nm. The AlGaN heterostructures were grown by metalorganic vapour phase epitaxy on a double growth and double high temperature annealed (DGA) AlN/sapphire templates. The Al mole fraction of the AlGaN quantum wells, quantum well barriers, and the n-AlGaN layer was modified with the objective of fabricating LEDs with peak emission wavelengths between 242 nm and 218 nm. On-wafer electroluminescence (EL) measurements at a dc current of 50 mA reveal a decline in the mean emission power from 0.7 mW for LEDs with wavelengths exceeding 230 nm to 0.01 mW for the 222 nm LEDs. To quantify the different contributions to the decrease in emission power and external quantum efficiency (EQE), the light extraction efficiency (LEE), radiative recombination efficiency (RRE) and current injection efficiency (CIE) was analysed. The LEE was determined using calibrated Monte Carlo ray-tracing simulations with the layer structure and the optical polarization of light emission as input parameters. A shift in the optical polarization of the emitted light from predominantly transverse electric to predominantly transverse magnetic was observed at a wavelength of 231 nm. The LEE was found to be the highest for 236 nm LED with 3.2 %, with a decrease of approximately 2.6 times for the 222 nm LEDs. Furthermore, pulsed EL measurements were conducted, and the resulting data were analysed using the Titkov-Dai fitting method. This enabled the determination of the RRE and CIE separately. The RRE_{max} decreased from 60 ± 5 % for 233 nm LEDs down to 22 ± 5 % for 222 nm LEDs which is a factor of roughly 2.7. The most significant impact on the reduction in emission power was observed in the CIE, which decreased by a factor of 11 from 234 nm LEDs (22 ± 3 %) to 222 nm LEDs (2 ± 1 %). Drift-diffusion simulations revealed that the drop is caused by an increased electron overflow into the p-type layers, which is a consequence of the reduced energy offset between the barriers and the AlN-EBL with decreasing wavelength.

PC-Mon-3 - Free and bound excitons in AlN

2. Physics and characterization

Felix Nippert[1]
Luca Sung-Min Choi[1], Nils Bernhardt[1], Auditee Majumder Momo[2], Ronny Kirste[3], Ramón Collazo[2], Zlakto Sitar[3], Markus R. Wagner[4]
[1] Technische Universität Berlin
[2] North Carolina State University
[3] North Carolina State University, Adroit Materials
[4] Technische Universität Berlin, Paul-Drude-Institut

Abstract text: Despite its technological relevance as a wide bandgap material for power and opto-electronics, the near band edge emission of AlN is poorly understood. We report on high-resolution photoluminescence spectroscopy of a high-quality c-plane homo-epitaxial MOCVD-grown AlN thin film, where several bound and free exciton transitions with linewidths below 500µeV are observed.

Due to strong exchange interaction, exciton transitions involving holes from the highest valence band (A,Γ_7) with Γ_1 spin-singlet, Γ_5 spin-triplet and (dipole-forbidden) Γ_2 symmetry are expected [1], but there is a dispute in the literature about the sign of the interaction energy *j*, and hence, the ordering of the Γ_1 and Γ_5 transitions[2,3]. The Γ_1 transition couples strongly to phonons and can be identified by its longitudinal and transverse exciton-polariton contributions, as well as phonon replicas involving the A_1/E_1 TO/LO modes. For positive *j*, the Γ_5 transition is found at slightly lower energies; we observe it 3.2meV below Γ_1^T. The temperature dependence of linewidth and intensity is consistent with a free exciton.

In addition, several bound excitons are observed, of which only the origin of one (Si^0X) has been clarified in the literature [4], which is observed here as the strongest line with a clear TES transition consistent with a donor binding energy of 65meV and a localization energy of 19meV. A second, strong emission line (labeled X_6 in Ref. [5]) with a localization energy of 12meV has seldomly been observed before [5,6], but is of similar intensity as Si^0X in our sample. In contrast to the latter, X_6 thermalizes rapidly with a 3.7meV activation energy and is not visible above 20K. This is also reflected in the lifetime of this transition, which rapidly decreases with temperature. The lifetime at very low temperatures is, however, extremely long compared to all other transitions, with around 3ns. This suggests that the origin is quite different to the Si^0X, i.e. not an exciton bound to a shallow donor, but rather possibly involving a dark state.

[1] Cho, Phys. Rev. B 14, 4463 (1976)

[2] Ishii et al., Phys. Rev. B 102, 155202 (2020)

[3] van Deurzen et al., APL Materials 11, 081109 (2023)

[4] Neuschl et al., Phys. Status Solidi B 249, 511 (2012)

[5] Ishii et al., Phys. Status Solidi RRL, 2400017 (2024)

[6] Feneberg et al., Phys. Status Solidi A 208, 1520 (2011)

PC-Mon-4 - High-Resolution Cathodoluminescence Imaging of AlGaN Deep-UV Quantum Wells

2. Physics and characterization

Kagiso Loeto[1]
Marcel Schilling[2], Tim Wernicke[2], Carsten Hartmann[3], Thomas Straubinger[3], Michael Kneissl[2], Jonas Lähnemann[1]
[1] Paul-Drude-Institut für Festkörperelektronik
[2] Technische Universität Berlin, Insitute of Solid State Physics
[3] Leibniz-Institut für Kristallzüchtung

Abstract text: High resolution cathodoluminescence (CL) imaging has significantly contributed to the understanding of point defect formation in InGaN quantum wells for blue light-emitting diodes (LEDs) [3]. The further advancement of deep-ultraviolet (DUV) LEDs based on AlGaN also requires a similar understanding of the point defects. This is crucial because the radiative recombination efficiency (RRE) of AlGaN DUV LED is limited by non-radiative recombination at point defects (PDs) which is apparent when analysing the RRE for samples with low threading dislocation densities (10^5 cm^{-2}). Currently, the spatial densities and behaviour of PDs in AlGaN DUV LEDs are not yet fully understood. This is because spatially resolved imaging remains a significant challenge and has not yet been achieved. Recent and novel work by Weatherly *et al.* has shown that individual PDs in InGaN quantum-wells (QWs) can be resolved using CL imaging when the sample and measurement conditions are carefully chosen to favour high spatial resolution [1].

We show for the first time that a similarly high spatial resolution can be achieved in CL imaging of AlGaN QWs grown on bulk AlN substrates. In CL, the spatial resolution is limited by the interaction volume which depends heavily on the acceleration voltage and the diffusion length of the carriers. Whereas the diffusion of carriers in a disordered ally such as AlGaN is suppressed at cryogenic temperature, the excitation volume poses a bigger challenge. These measurements are made possible by a highly stable electron source that can operate at very low acceleration voltages (350 V) and picoampere beam currents. The low acceleration voltage requires also specially designed samples consisting of an ultra-thin (1 nm) quantum-well with thin (5 nm) barriers to further limit carrier diffusion and the excitation volume respectively. Through measurements performed at 1 kV and 45 K on 255 nm emitting QWs, we have achieved a lateral spatial resolution of 30 nm, exceeding the 76 nm reported by Weatherly *et al*. [1] and estimated a PD density on the order of 10^{16} cm^{-3}. Through this technique, the quantification of PD densities in AlGaN QWs with varying aluminium content can now be shown, along with their beam current, temperature, and time-resolved characteristics.

[1] Weatherley et al 2021 Nano Letters 21 5217–5224

Radio Frequency Devices 2 (Enhanced Performance)

2025-07-07
13:30 - 15:00
Radio Frequency Devices 2 (Enhanced Performance)

ED-Mon-5 - Advancing RF GaN HEMT Technology: Innovations in Buffer Engineering for Enhanced Performance and Robustness

4. Electronic devices

FARID MEDJDOUB[1]
[1] CNRS-IEMN

Abstract text: Advancing RF GaN HEMT Technology: Innovations in Buffer Engineering for Enhanced Performance and Robustness

Advancing RF GaN HEMT technology is essential to meet the growing demands of next-generation RF power devices, particularly in the mm-wave spectrum, where high efficiency, robustness, and superior output power density are critical. Highly scaled GaN transistors, however, face significant challenges that limit their performance. Efficiency in state-of-the-art GaN HEMTs is typically constrained to 50% or below in the millimeter-wave range, especially at power densities exceeding 3 W/mm. These limitations stem from reduced power gain, increased trapping effects, and diminished electron confinement as device dimensions are scaled down. Furthermore, reliability remains a concern for sub-150 nm GaN devices, hindering their widespread adoption in demanding applications. This talk highlights innovative approaches to overcoming these challenges through advanced buffer and epilayer engineering. By leveraging highly scaled epitaxial heterostructures, the proposed solutions aim to enhance electron confinement, mitigate trapping effects, and improve thermal management, thereby boosting device performance and robustness. These advancements are poised to enable GaN HEMTs to achieve unprecedented efficiency and power density in the mm-wave regime. The integration of these cutting-edge epitaxial designs not only addresses current limitations but also paves the way for the development of reliable, high-performance GaN-based transistors, essential for next-generation communication systems, radar, and other RF power applications. This work underscores the critical role of material and structural innovations in pushing the boundaries of GaN HEMT technology.

ED-Mon-6* - Buffer engineering to boost the blocking voltage of GaN High Electron Mobility Transistors on sapphire

4. Electronic devices

Adrien Bidaud[1]
Etienne Okada[1], Katir Ziouche[1], Ajit Paranjpe[2], Farid Medjdoub[1]
[1] CNRS, Institut d'Electronique, de Microélectronique et de Nanotechnologies, Lille, France
[2] Prima Innotech LLC, Basking Ridge, New Jersey, USA

Abstract text: In this study, we present a state-of-the-art trade-off between on-resistance (R_{ON}) and breakdown voltage in GaN HEMTs grown on sapphire substrates. This advancement was realized through the strategic integration of an AlGaN back barrier (BB) and precise carbon doping of the buffer layer. Our results demonstrate that combining a high carbon concentration in the buffer layer with an AlGaN BB enables low R_{ON} while achieving a blocking voltage close to 5 kV, even with ultrathin buffer layers (< 1µm thickness) without the need for gate dielectrics or field plates.

Four distinct epitaxial structures were designed: two featured a 500 nm highly carbon-doped GaN buffer and two utilized a bilayer buffer consisting of a lower iron-doped GaN layer and an upper medium carbon-doped layer. Each pair included one structure with a 350 nm unintentionally doped GaN channel (without a back barrier) and another with a 150 nm unintentionally doped GaN channel incorporating a 100 nm AlGaN BB containing 6% aluminum. Hall effect measurements confirmed similar 2DEG properties, ensuring consistent performance.

The buffer breakdown performance was assessed using isolated ohmic contacts. Despite its reduced thickness, the buffer with high carbon doping exhibits significantly enhanced voltage handling capabilities, underscoring that doping concentration plays a more critical role in determining blocking voltage performance than physical thickness.

Breakdown voltage measurements for transistors with gate to drain distances of 10 µm to 40 µm were conducted. The highest carbon-doped buffer delivers superior breakdown voltages, while lower carbon concentrations led to increased off-state leakage currents and premature device failure. Remarkably, the incorporation of the AlGaN BB significantly improved breakdown voltage while effectively reducing leakage current. This enhancement is attributed to the AlGaN BB's ability to strengthen 2DEG electron confinement under high electric fields. Importantly, all structures exhibited low R_{ON} owing to the favorable 2DEG properties.

These findings establish GaN-on-sapphire HEMTs as a cost-effective and competitive solution for high-voltage applications. Further work will focus on further optimizing the back barrier design and carbon-doping concentrations as well as investigating trapping effects to unlock additional performance improvements.

ED-Mon-7* - High Temperature Modeling of GaN HEMTs for RF Amplifier Design at 500°C

4. Electronic devices

Ashley Goodnight[1]
John Niroula[1], Matthew A. Taylor[1], Pradyot Yadav[1], Tomás Palacios[1]
[1] Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract text: High temperature (HT) electronics are crucial for a multitude of extreme environments within the space, automotive, geothermal, and aerospace industries. Gallium nitride (GaN) has emerged as a promising candidate for HT electronics due to its wide bandgap and resulting low intrinsic carrier concentration [1]. However, a major challenge impeding the development of HT GaN circuits is the lack of temperature-dependent device models. Such frameworks for computer-aided design are critical in the design process to ensure high first-pass yields and reduce time-to-market. In this work, we demonstrate a compact model for GaN-based devices from 25ºC to 500ºC, which enabled the design of an RF amplifier optimized for HT operation. To the best of the authors' knowledge, this is the first design and simulation of a GaN RF amplifier at 500ºC with an experimentally-calibrated device model.

GaN high electron mobility transistors with gate lengths from 100 nm to 1 μm were fabricated and electrically characterized up to 500ºC. From these DC and RF empirical results, key device parameters were extracted at each temperature. The observed temperature-dependent trends were incorporated into an MIT Virtual Source GaN FET model. The model was imported into Keysight ADS to simulate a single-stage common-source RF amplifier tuned for broadband operation at 500ºC from 2.5 to 3.5 GHz, an important frequency band used for mobile, satellite, and radar systems. The proposed amplifier demonstrates a simulated performance with a small-signal gain above 18 dB, return losses over 10 dB, and 0.8 dBm peak output power at 3.5 GHz. Overall, this work establishes a clear methodology for HT device characterization and GaN-based transistor compact modeling, facilitating easier temperature-dependent circuit design.

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Acknowledgements

Device fabrication and characterization was conducted at MIT.nano. This work was sponsored in part by the Air Force Office of Scientific Research (AFOSR) under award no. FA9550-22-1-0367 and Lockheed Martin Corporation under award no. 025570-00036.

ED-Mon-8* - High-Power Si-Based AlN/GaN MISHEMTs with Composite Al2O3/SiNx layer for Millimeter-Wave Applications: Achieving 7.8 W/mm Power Output

4. Electronic devices

Jing Yuan[1]
Xiaojuan Chen[1], Ying Luo[1], Ke Wei[1], Yankui Li[1], Lizhao Cen[1], Weijun Luo[2], Sen Huang[1]
[1] Institute of Microelectronics of Chinese Academy of Sciences, Beijing, China
[2] Institute of Microelectronics of Chinese Academy of Sciences, Beijing , China

Abstract text: The rapid deployment of millimeter-wave (mm-wave) technologies for 5G/6G communication, automotive radar, and satellite systems demands high-power, high-efficiency semiconductor devices ,especially GaN devices, capable of operating at frequencies beyond 30 GHz. While GaN-on-SiC devices have dominated high-frequency power electronics, their prohibitive cost and limited scalability hinder widespread adoption in consumer and infrastructure markets. Silicon-based GaN (GaN-on-Si) devices emerge as a compelling alternative, offering CMOS-compatible fabrication, cost-effective scalability, and competitive performance at mm-wave frequencies. However, challenges such as interfacial defects, current collapse, and thermal limitations in GaN-on-Si have historically restricted their power density and reliability in high-frequency regimes.

In this work, building on the Si-based SiN_x (2 nm)/AlN(5 nm)/GaN MISHEMTs, we employed silicon substrate to reduce the manufacturing cost, the thin AlN barrier to suppress the short-channel effect while avoiding etching damage, simplifying the process. Meanwhile, this work employed plasma-enhanced atomic layer deposition (PEALD) to epitaxially grow Al_2O_3 and plasma-enhanced chemical vapor deposition (PECVD) to deposit SiN_x dielectrics for secondary passivation. This approach addresses the insufficient passivation provided by sub-3 nm SiN_x layer, which fail to provide good enough passivation for current collapse suppression in mm-wave MISHEMTs, reduces the interface state and compensates for the lattice mismatch of the material. The optimized device, featuring a gate width of 2×75 μm and a source-drain spacing of 2.4 μm, achieved a breakdown voltage of 148 V, a current collapse of less than 6%. Besides, the devices yielded both high powercapacity third-Order Intermodulation Output Power (OIP_3) of 37.8 dBm at 30 GHz and high P_{out} (7.8 W/mm) at V_{ds} of 35 V in pulsed-wave (PW) power measurements with a duty cycle of 1:10 at optimal P_{out} impendence.

In summary, this work through the collaborative design of a low-cost silicon substrate, thin AlN barrier layer, and Al_2O_3/SiN_x composite layer, achieves a collaborative optimization of simplified process, high performance and high reliability. It offers a competitive solution for 5G millimeter-wave communication.

ED-Mon-9 - High Power Linearity AlN/GaN/InGaN Coupling-Channel High Electron Mobility Transistors at 30 GHz

4. Electronic devices
Hao Lu[1]
Ling Yang[1], Bin Hou[1], Xiaohua Ma[1], Yue Hao[1]
[1] School of Microelectronics, Xidian University, Xi'an, City China

Abstract text: AlGaN/GaN-on-SiC high-electron-mobility transistors (HEMTs) have emerged as a focal point in advanced semiconductor research, primarily due to their exceptional power handling capabilities, which surpass those of conventional Si CMOS and III-V compound materials. With the escalating demands of modern communication systems, there is an urgent need to enhance the performance metrics of power amplifiers (PAs), specifically their output power and linearity. While our prior investigations into AlGaN/GaN HEMTs have yielded notable achievements, including power densities exceeding 33 W/mm in the X-band and 14 W/mm in the Ka-band, conventional AlGaN/GaN heterostructures face significant limitations in meeting the stringent requirements of millimeter-wave applications.

In this presentation, we introduce a novel multiscale vertical scaling-down epitaxial structure design, featuring an AlN/GaN/InGaN architecture, specifically engineered to address key challenges in millimeter-wave (mmWave) applications. This design aims to mitigate the short-channel effect, strengthen quantum well confinement, and improve thermal management, as illustrated in Figs. 1(a) and 1(b). The incorporation of coupling channel engineering, as depicted in Fig. 1(c), demonstrates a significant reduction in dynamic source resistance, leading to enhanced transconductance (g_m) and RF linearity. Furthermore, the AlN/GaN/InGaN coupling channels achieve an exceptional subthreshold slope of less than 60 mV/dec, as shown in Fig. 2, with the underlying hot electron transfer mechanism providing a theoretical foundation for these performance gains.

As shown in Fig. 3, a two-tone test was conducted at 30 GHz, yielding a remarkable linearity figure of merit ($OIP3/P_{DC}$) exceeding 12 dB. As shown in Table I, this result positions our CC-HEMTs favorably against the latest linearization technologies reported in prior studies. Additionally, we will present advancements in low-resistive AlN ohmic contacts and low-leakage gate oxidation techniques, alongside the implementation of a high-speed thin InGaN channel to further enhance quantum confinement. These cutting-edge innovations collectively offer a highly competitive epitaxial solution for high-power, wide-frequency-range mmWave applications, paving the way for next-generation communication systems.

Advanced lasers

2025-07-07
13:30 - 15:00
Advanced lasers

OD-Mon-5 - Recent progress in GaN photonic-crystal surface-emitting lasers (PCSELs)

3. Optical devices

Susumu Noda[1]
[1] Institute for Advanced Study, Kyoto University, Kyoto 606-8510, Japan

Abstract text: Short-wavelength (blue-violet-to-green) lasers with high power and high beam quality are required for various applications including the machining of difficult-to-process materials, high-brightness illuminations, and underwater light detection and ranging (LiDAR). Promising light sources for such applications are wide-bandgap GaN-based photonic-crystal surface-emitting lasers (PCSELs) [1-3], which are based on two-dimensional resonance at a singularity point of the photonic crystal. In the present talk, after a brief review of PCSELs based on other material systems [4,5], recent developments of GaN-based PCSELs will be discussed. It will first be shown that optimization of the device layer structure is essential to enhance the 2D photonic-crystal resonant effect for a GaN-based system, whose refractive index contrast is smaller than the other material systems. Next, the importance of developing a nano-fabrication method for realizing GaN/air structures with sufficiently small disorders will be shown. Then, the optimization of a unit cell structure to realize a single-lobed and narrow-divergence beam will be discussed; for example, a double-lattice structure, whose two lattices are separated appropriately, is important to enhance the extraction efficiency of lasing light in the direction normal to the device surface. With these optimizations, watt-class (>1 W) output power and a circular, single-lobed beam with a very narrow (0.2°) divergence angle have been realized for GaN-based PCSELs. Even unique applications such as underwater LiDAR systems have been achieved. The current issues of GaN-PCSELs are briefly referred to and the talk will be concluded with their future prospects.

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OD-Mon-6* - Understanding losses and mode selection in finite-sized ultraviolet-C photonic-crystal surface-emitting lasers

3. Optical devices

Dogukan Apaydin[1]
Lars Persson[1], Moritz Riedel[2], Sarina Graupeter[3], Lukas Uhlig[2], Joachim Ciers[1], Tim Wernicke[3], Michael Kneissl[3], Ulrich Theodor Schwarz[2], Åsa Haglund[1]
[1] Chalmers University of Technology, Department of Microtechnology and Nanoscience, 41296 Gothenburg, Sweden
[2] Chemnitz University of Technology, Institute of Physics, 09126 Chemnitz, Germany
[3] Technische Universität Berlin, Institute of Solid State Physics, 10623 Berlin, Germany

Abstract text: We have recently demonstrated the first optically pumped ultraviolet-C (λ<280 nm) photonic-crystal surface-emitting laser (PCSEL) showing narrow linewidth single mode operation and a narrow far field. Here we show how threshold and far-fields are affected by the PCSEL size and lattice constants and compare measured to simulated characteristics to gain a better understanding of the trade-offs between threshold and high-quality far-fields. We investigate the total losses both experimentally by measuring threshold and through 3D coupled-wave theory (3D-CWT) simulations for PCSELs with sizes of 150 to 850 unit cells (Ø~20 μm to ~116 μm) and lattice constants between 133 and 142 nm for a 500-unit cell device. Experimentally, we find that the threshold pump power density increases exponentially with decreasing PCSEL size. Simulations confirm this trend that is mainly due to an increase in lateral losses for the six modal branches (A, B_1, B_2, C, D_1, D_2). For a 550-unit cell device (Ø~75 μm), the B and C modes experience the lowest losses. To identify which mode that lases, polarization-resolved far-fields can be very useful, and here indicate lasing in the B_1 mode. The PCSEL size also affects the spectral properties and far-field. Small enough PCSELs (Ø ≤ 68.5 μm) with a lattice constant of 137 nm seem to lase in the B_1 mode producing a narrow doughnut-shaped far-field centered around zero degrees. In contrast, larger PCSELs (Ø >75 μm) lase in multiple modes, yielding a degraded far-field with sixfold symmetry. We attribute this to 1D coupling effects, which may be under-coupled (high lateral losses) in small PCSELs and over-coupled (low lateral losses) in larger ones. A similar transition is observed when varying the lattice constant for a fixed PCSEL diameter (500 unit cells, ~70 μm Ø). For lattice constants between 134 to 137 nm, devices seem to lase in the B_1 mode, while for lattice constant >138 nm, 1D lasing emerges which distorts the far-fields. The lattice constant also strongly affects the threshold since it shifts the full band structure which affects the modes spectral overlap with the gain peak and thereby the modal gain. In summary, the choice of both PCSEL size and lattice constant results in a trade-off between obtaining low threshold and high-quality far-fields and developing designs to lower the threshold for smaller-sized PCSELs will be important.

OD-Mon-7* - Losses in deep-UV Photonic Crystal Surface Emitting Lasers: finite-size coupled-wave theory simulations versus semi-analytical approximation

3. Optical devices

Moritz Riedel[1]
Lukas Uhlig[1], Lars Persson[2], Åsa Haglund[2], Ulrich T. Schwarz[1]
[1] Chemnitz University of Technology, Chemnitz.Germany
[2] Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg, Sweden

Abstract text: A photonic-crystal surface-emitting laser (PCSEL) has been demonstrated first in the infrared and recently also in the blue [1] and green [2] spectral region. Operating at the Gamma point of the photonic crystal dispersion, a PCSEL can deliver high output power into a single mode operation with low-divergent far-field. We recently demonstrated optically pumped deep-UV PCSELs (λ=279 nm) with a photonic crystal consisting of circular holes in a hexagonal lattice etched into the top AlN cladding.

To understand and optimize these devices it is important to be able to simulate modal losses for finite-sized PCSELs. Simulations of the infinite PCSELs are straightforward and can provide for example the band structure, but they fail in the prediction of radiative and lateral propagation losses that are strongly influenced by PCSEL size. The classical way to simulate finite area PCSELs is to use a coupled wave theory (CWT) approach, including higher order coupling terms [3,4].

Using the CWT approach, we calculate radiative and lateral losses for deep-UV PCSELs with varying filling factor as a function of the radius of the PCSEL. Furthermore, we compare those losses to those obtained by another model in which losses are estimated from the dispersion curves for an infinite PCSEL, where lateral and vertical losses are given by integration over the finite distribution in k-space. This approach – combining a numerical simulation of the band structure with analytical expressions for the losses – provides semi-analytical expressions for vertical and lateral losses in the limit of large PCSEL diameters.

We furthermore apply this semi-analytical approach to both the CWT model and a guided mode expansion (GWE) simulation of the infinite PCSEL, in order to estimate the impact of the respective approximation on predictions for finite-sized PCSEL. The presented elegant way to estimate losses for finite size PCSEL enables a quantitative interpretation of our experimental observations on mode selection and thresholds in deep-UV PCSEL, as well as provide us with an efficient tool to optimize the structure.

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OD-Mon-8 - Proposal of a Novel Low-Refractive-Index Double-Layer Structure Formed by Electrochemical Etching Applicable to GaN Photonic Crystals

3. Optical devices

Akihiko Kikuchi[1]
Mirai Akimoto[1], HInaki Sugiura[1]
[1] Sophia University, Tokyo, Japan

Abstract text: A method for forming high-density nanopores (NP) in heavily doped n^+-GaN layers using electrochemical etching (ECE) as a low-refractive-index material for GaN-based optical devices has attracted attention. We have found out a new ECE-based nanostructure that can be applied to GaN photonic crystals (PhCs) composed of precise nanoholes, achieving high optical confinement and suitability for current injection.

First, we formed a topological PhC structure with equilateral triangular nanoholes, arranged in a modulated honeycomb pattern, in a 152 nm thick low-doped pn junction core layer sandwiched by GaN layers with an InGaN MQW active layer. The side lengths of the triangular nanoholes were varied from 170 to 100 nm to control the photonic bandgap wavelength. These PhC structures were fabricated using a low-damage precise etching method (HEATE) that utilizes hydrogen-assisted thermal decomposition of GaN in a high-temperature, low-pressure hydrogen atmosphere.

Next, we processed a 1500 nm thick n^+-GaN layer placed directly below the core layer using ECE with oxalic acid solution under specific conditions. This resulted in the formation of a transfer structure with a depth of approximately 600 nm, maintaining the PhC structure and expanding the shape of the triangular holes directly below the PhC core layer, with an NP layer having random vertical nanoholes formed beneath it. We refer to this structure as a double-layer structure. Under different conditions, only an NP layer with vertical nanoholes was formed directly below the PhC.

Optical measurements and 3D-FDTD analysis of these two types of structures confirmed that the formation of a photonic bandgap and the manifestation of topological properties were observed only in the double-layer structure formed below the PhC. These results indicated the superiority of the newly proposed double-layer structure formed by ECE.

OD-Mon-9* - Room temperature lasing from a bound state in the continuum confined in a GaN subwavelength grating

3. Optical devices

Tomasz Fąs[1]
Emilia Pruszyńska-Karbownik[1], Marta Sawicka[2], Oliwia Gołyga[2], Anna Feduniewicz-Żmuda[2], Grzegorz Muzioł[2], Mateusz Słowikowski[3], Czesław Skierbiszewski[2], Tomasz Czyszanowski[4], Jan Suffczyński[1]
[1] Faculty of Physics, University of Warsaw, Warsaw, Poland
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland
[3] CEZAMAT, Warsaw University of Technology, Warsaw, Poland
[4] Institute of Physics, Łódź University of Technology, Łódź, Poland

Abstract text: This study demonstrates room-temperature lasing around 440 nm using a nanoscale laser based on bound states in the continuum (BICs). The device consists of subwavelength gratings etched into gallium nitride (GaN), below which indium gallium nitride (InGaN) quantum wells and a low-refractive-index porous GaN layer are placed. GaN has been selected for its high refractive index, low visible-light absorption, and robust thermal properties, making it ideal for visible photonic applications.

BICs, which arise in periodic structures via destructive interference of radiative channels, coexist with a continuum of radiating states and exhibit exceptionally high quality (Q) factors. Subwavelength gratings — diffractive structures with a period smaller than the wavelength of light — are employed here as a platform to confine BIC modes. The GaN sample with InGaN QWs was fabricated using Molecular Beam Epitaxy. The gratings were made using electron beam lithography and dry etching, while the porous GaN substrate was fabricated via electrochemical etching.

Optical characterization of the nanolaser was performed by angle-resolved photoluminescence spectra under excitation by a 375-nm femtosecond pulsed laser. Below the lasing threshold, the spectra exhibited a rich structure of optical modes, consistent with the theoretical predictions of BIC-driven light confinement. As the pump power was increased, a single, narrow, dominant emission peak emerged at Γ-point at 443 nm, accompanied by a nonlinear increase in output intensity, confirming the onset of laser action.

The tunability of the laser emission was explored by examining hundreds of gratings with varying periods and stripe widths. This investigation highlights the device's potential for customization and adaptability. The compact nature of this room-temperature nanolaser, combined with its robust performance, positions it as a promising platform for future research and a wide range of photonic applications.

Bulk GaN and AlGaN

2025-07-07
13:30 - 15:00
Bulk GaN and AlGaN

GR-Mon-A1 - Production-ready, high-quality GaN on GaN epitaxy by QF-HVPE up to 6”

1. Growth

Shota Kaneki[1]
Taichiro Konno[1], Hisashi Mori[1], Hajime Fujikura[1]
[1] Sumitomo Chemical Co., Ltd., Hitachi, Japan

Abstract text: For commercialization of GaN-on-GaN power devices, a cost-effective growth method of large-sized wafer is crucial, although the low growth rate of a conventional metalorganic vapor phase epitaxy (MOVPE) as well as a lack of large sized GaN-on-GaN wafer make its establishment difficult. Severe C-induced carrier compensation peculiar to the MOVPE growth also becomes an obstacle to have high enough voltage blocking capability in such GaN power devices.

Our recently developed quartz-free hydride vapor phase epitaxy (QF-HVPE) technology can solve these issues of low growth rate and C-contamination of the MOVPE due to its high growth rate over 100 μm/h and availability of high quality GaN crystal with extremely low Si, O and C concentrations below the mid-10^{14}/cm^3 ranges. The 2”-sized GaN on GaN epitaxial wafers grown using a proto-type QF-HVPE reactor exhibited excellent material qualities including a record high room temperature mobility of 1,480 cm^2/Vs, a record high mobility of 14,300 cm^2/Vs,[1] and extremely high photoluminescence internal quantum efficiency of 21.7%.[2]

In this talk, we will present our recent results of GaN-on-GaN epitaxy made using a newly developed mass-production type QF-HVPE reactor with 6” growth capability. Its well-designed, sophisticated reactor has enabled growth of GaN layers having further improved material qualities.

Main results are listed below:

- High thickness uniformity; ex.) Standard deviation, s =3.4% for 4”.
- High electron concentration uniformity; ex.) s =3% for 4”.
- Wide range of Si-doping control within 10^{14} to 10^{19} /cm^3
- Capability of 6” GaN on GaN epitaxy.
- Record high room temperature mobility of 1,591 cm^2/Vs at 295 K.,
- Record high maximum mobility of 18,175 Vs/cm^2 at 35 K.

This presentation is based on results obtained from a project, JPNP21005, subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

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GR-Mon-A2 - Perspectives on the Growth of $Al_xGa_{1-x}N$ Alloy by the Ammonothermal Method

1. Growth

Robert Kucharski[1]
Tomasz Sochacki[1], Karolina Grabianska[1], Magdalena Zajac[1], Petro Sadovyi[1], Arianna Jaroszynska[1], Jan Weyher[1], Lutz Kirste[2], Michal Bockowski[1]
[1] Institute of High Pressure Physics Polish Academy of Sciences, Warsaw, Poland
[2] Fraunhofer Institute for Applied Solid State Physics (IAF), Freiburg, Germany

Abstract text: Aluminum Gallium Nitride ($Al_xGa_{1-x}N$) is a key alloy in GaN-based transistor architectures, particularly High Electron Mobility Transistors (HEMTs) [1]. Its combination with GaN enables applications in radio-frequency and high-power electronics, offering high switching speeds, superior breakdown voltage, and low ON resistance. However, the performance of these heterostructures is often limited by growth on foreign substrates like GaN/sapphire template, which leads to lattice mismatches, thermal dissipation issues, and residual strain, ultimately affecting device efficiency. Nevertheless, the crystallization of bulk $Al_xGa_{1-x}N$, even with a low content of Al component, still remains a challenge.

Currently, ammonothermal method is used for GaN crystallization, particularly for highly conductive (n-type) and semi-insulating. Two-inch Am-GaN substrates of exceptional structural quality are available, featuring crystallographic flatness, a uniform off-cut angle, and a threading dislocation density below 5×10^4 cm^{-2} [2]. This technology extends beyond GaN crystallization. Through the modification of growth conditions $Al_xGa_{1-x}N$ alloy growth becomes possible as well [3].

This study explores the potential of ammonothermal $Al_xGa_{1-x}N$ crystallization, including direct growth attempts on a GaN seed. Additionally, it examines $Al_xGa_{1-x}N$ crystal growth on a slender GaN seed, where edge nucleation followed by lateral crystallization was induced. Both [000-1] growth and lateral overgrowth were analyzed in detail. The Energy Dispersive Spectroscopy analysis of cross-sections from laterally grown crystals will be used to determine the alloy composition as a function of crystallization direction. Furthermore, the study investigated the influence of Al in the growth environment on $Al_xGa_{1-x}N$ crystallization, with a particular focus on the formation of low-energy crystallographic planes. Additionally, findings on dislocation propagation in various crystallographic directions will be presented. The proposed approach enabled the growth of bulk $Al_xGa_{1-x}N$ with an Al content ranging from 5 to 7 atomic %, and with (including) dislocation-free regions.

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GR-Mon-A3 - Effect of temperature on high-speed growth of GaN using oxide vapor phase epitaxy

1. Growth
Shigeyoshi Usami[1]
Daisuke Yamada[1], Ritsuko Higashiyama[1], Masayuki Imanishi[1], Junichi Takino[2], Tomoaki Sumi[2], Yoshio Okayama[2], Masahiko Hata[3], Masashi Isemura[4], Yusuke Mori[1]
[1] The University of Osaka
[2] Panasonic Holdings Corporation
[3] Itochu Plastics Inc.
[4] Sosho-ohshin Inc.

Abstract text: Reducing the cost of GaN substrates requires the production of ingots via high-speed and long-term growth. We propose an oxide vapor phase epitaxy (OVPE) method as a growth technique for GaN that enables long-term growth[1]. In this method, Ga_2O is used as the group-III source, preventing the formation of solid byproducts, such as NH_4Cl, in the exhaust section and theoretically enabling long-term growth. However, in the OVPE method, increasing the supply of Ga_2O and NH_3 to enhance the growth rate leads to excessive oxygen doping from Ga_2O ($>3\times10^{21}$ cm^{-3}), significantly degrading the crystal quality. Reports have suggested that increasing the hydrogen concentration in the carrier gas and the growth temperature are effective in reducing the oxygen concentration in GaN[2]. In our previous study, we demonstrated that increasing the hydrogen concentration allows for a growth rate of up to 600 μm/h without compromising crystal quality[3]. In this study, we investigated the effects of temperature on high-speed growth using the OVPE method.

The conventional and elevated growth temperatures were set to 1286 ℃ and 1320 ℃, respectively. The Ga_2O flow rate was fixed at approximately 110 sccm, whereas the NH_3 flow rate was varied from 450 to 1200 sccm. The growth duration was 15 min. At both temperatures, the growth rate increased with the NH_3 flow rate. However, at 1286 ℃, crystal quality deterioration occurred when the NH_3 flow rate exceeded 900 sccm. In contrast, at 1320 ℃, no deterioration in crystal quality was observed even at an NH_3 flow rate of 1200 sccm, and the growth rate exceeded 900 μm/h. Oxygen in GaN substitutes for nitrogen sites, and increasing the NH_3 flow rate generally reduces the oxygen concentration. However, at 1286 ℃, the oxygen desorption rate was insufficient, leading to excessive oxygen incorporation as the growth rate increased. As oxygen desorption is enhanced at higher growth temperatures, the deterioration of crystal quality was suppressed at 1320 ℃ even at a higher growth rate. These findings indicate that using a higher growth temperature in the OVPE method enables high-speed growth while maintaining crystal quality.

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GR-Mon-A4* - The challenges of AlGaN growth in Halide Vapor Phase Epitaxy

1. Growth

Arianna Jaroszynska[1]
Karol Pozyczka[1], Petro Sadovyi[1], Robert Kucharski[1], Karolina Grabianska[1], Lutz Kirste[2], Robert Czernecki[1], Michal Bockowski[1], Tomasz Sochacki[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland
[2] Fraunhofer Institute for Applied Solid State Physics (IAF), Freiburg, Germany

Abstract text: Aluminum Gallium Nitride ($Al_xGa_{1-x}N$) is a ternary alloy used in gallium nitride (GaN) based transistor architectures such as the High Electron Mobility Transistor (HEMT) [1]. The combined electric properties of $Al_xGa_{1-x}N$ and GaN make the aforementioned heterostructures fit for applications in devices operating at radio frequency and high power electronics. The $Al_xGa_{1-x}N$/GaN architectures are renowned for fast switching, high breakdown voltage and low ON resistance. However, the potential of these architectures is limited by the growth on foreign substrates, usually GaN on sapphire. This results in less than optimal device parameters related to, among other things, growth defects and suboptimal thermal distribution. If native (or near-native) substrates are used, the negative aspects of heteroepitaxy could be mitigated and a better performing, strain-free $Al_xGa_{1-x}N$ device could be obtained. Stress reduction brings many advantages to the functionality of semiconductor devices such as longer device lifespan and higher breakdown voltages. Halide vapor phase epitaxy (HVPE) remains one of the preferential methods to grow doped, and undoped, GaN crystals [2]. Based on the data published in the scientific literature, it was determined that the growth of $Al_xGa_{1-x}N$ alloy was possible in thermodynamic conditions present within an HVPE reactor as well [3]. In this work, the authors present challenges that had to be overcome during their efforts to crystallize a freestanding $Al_xGa_{1-x}N$ crystal. Firstly, the efforts to optimize morphology and Al content of $Al_xGa_{1-x}N$ layers grown on GaN/Al_2O_3 templates will be discussed along with the key parameters of growth. Layers with step-flow morphology and Al content (up to 10 at.%) will be presented. Next, $Al_xGa_{1-x}N$ growth on misoriented GaN seeds (0.5° to 4° towards the m-plane), will be shown in order to discuss the impact of initial substrate misorientation on the post-growth morphology, growth rate and structural quality as well as Al incorporation. Bormann effect which appears in samples of notably high crystalline quality will be presented. Perspectives for obtaining free-standing $Al_xGa_{1-x}N$ will be discussed.

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GR-Mon-A5 - Suppression of Polycrystals During GaN Crystal Growth in Na-flux Method under the Higher Temperature and the Higher Nitrogen Pressure Conditions

1. Growth

Tomoki Tashiro[1]
Masayuki Imanishi[1], Shogo Washida[1], Kosuke Murakami[1], Shigeyoshi Usami[1], Mihoko Maruyama[1], Masashi Yoshimura[2], Yusuke Mori[1]
[1] Graduate School of Engineering, The University of Osaka, Japan
[2] Institute of Laser Engineering, The University of Osaka, Japan

Abstract text: In the Na-flux method, large-diameter and high-quality GaN substrates can be fabricated by combining the multi-point seed (MPS) method with the flux-film-coated (FFC) technique which planarizes the crystal surface [1]. However, it has been reported that GaN crystals on MPS substrate (sub.) are difficult to grow because the seed crystals have a small surface area [2]. To enhance growth, highly supersaturated conditions are usually applied during the initial growth stage, but those conditions often lead to formation of polycrystals in the crucible. In this study, we investigated the possibility of achieving growth on MPS sub. while suppressing formation of polycrystal under higher N_2 pressure conditions (5 MPa) and lower N_2 pressure conditions (2 MPa) compared to the conventional pressure range of 3–4 MPa. Temperature conditions were also controlled to make supersaturations of the flux equal.

The growth was performed for 48 hours at N_2 pressure of 2 MPa and temperature of 850°C (2 MPa/850°C) and 5 MPa/900°C using the MPS and template sub. We measured weight of crystals and calculated the conversion rate of source Ga to GaN crystal based on weight of grown crystals. We defined the conversion rate as yield and considered the yield of crystals on template sub. is an indicator of supersaturation. It was found that the yields of crystals on the template sub. were similar under both conditions, but crystal grew on MPS sub. at 5 MPa/900°C but not at 2 MPa/850°C. Therefore, we expected that crystal growth on MPS sub. can be realized under high-temperature and high-pressure conditions without polycrystals.

Subsequently, crystals were grown on MPS sub. by applying high-temperature and high-pressure conditions to the typical FFC process. The yield of the crystal grown on MPS sub. was 35.7%, without polycrystal formation at 5 MPa/900°C. In comparison, under conventional condition (3 MPa/870°C), the yield of on-substrate crystal was 33.5%, while the yield of polycrystal was 11.7%. These results suggest that polycrystal is more suppressed under high-temperature and high-pressure conditions compared to other conditions with equivalent supersaturation.

References

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BN and novel nitrides with B

2025-07-07
13:30 - 15:00
BN and novel nitrides with B

GR-Mon-B5 - Growth of hexagonal boron nitrides on non-catalytic substrates by MOCVD and their applications

1. Growth

Jong Kyu Kim[1]
Seokho Moon[1], Jiye Kim[1], Si-Young Choi[1], Bernard Gil[2], Guillaume Cassabois[2]
[1] Pohang University of Science and Technology(POSTECH), Pohang, Republic of Korea
[2] CNRS-Universite de Montpellier, Montpellier, France

Abstract text: Hexagonal boron nitride (h-BN) has recently attracted a great attention due to its fascinating optical, electrical, and thermal properties, and promising applications across the fields of photonics, quantum optics, and electronics. However, mechanically exfoliated bulk h-BN and h-BN films grown on catalytic metal substrates have been mainly used to study the fundamental properties, lacking in scalability for practical implementation of h-BN. Here, we present a scalable approach for growing high-quality h-BN on various non-catalytic substrates, including Si and epitaxial III-Nitrides, via metal-organic chemical vapor deposition (MOCVD), and its various electronics and photonics applications.

For implementation of wafer-scale h-BN films into current state-of-the-art Si-based microelectronics technology, we demonstrate the conformal growth of sp^2 hybridized few-layer h-BN over an array of Si-based nanotrenches with 45 nm pitch and the aspect ratio of ~ 7:1. NEXAFS spectroscopy and DFT calculations reveal that the B-O bonds formed on the non-catalytic SiO_2 surface act as nucleation sites for the formation of mixed sp^2-and sp^3-hybridized BON2 and BN3, facilitating the conformal growth of sp^2-hybridized h-BN with excellent step coverage.

In addition, we demonstrate the scalable use of uniform h-BN van der Waals passivation layer on a 2-inch AlGaN/GaN high-electron mobility transistor (HEMT) wafer via MOCVD. Structural, spectroscopic, and theoretical analyses revealed an atomically sharp heterointerface between the h-BN layer and the AlGaN surface, underscoring the potential of h-BN for advanced device passivation. Finally, it was found that under specific MOCVD growth conditions, a unique few-layer h-BN film can be grown on GaN substrates, in which the few-layer h-BN film is suspended on GaN nanoneedles. The combination of state-of-the-art microscopic and spectroscopic analyses revealed that the suspended h-BN films exhibit unprecedented atomic stacking. The mechanism underlying the formation of unique atomic stacking will be investigated through structural and electrical characterizations, as well as theoretical modeling. Our findings unveil new perspectives for the scalable synthesis of engineered h-BN polytypes.

GR-Mon-B6 - Ammonothermal Growth of Rhombohedral Boron Nitride

1. Growth
Jacob Dooley[1]
Nathan Stoddard[1], Kai Landskron[1], **Siddha Pimputkar**[1]
[1] Lehigh University, USA

Abstract text: Boron nitride (BN) has advantageous physical and electrical properties for (opto-)electronic applications, yet growing large area, bulk single crystals has proven challenging. These materials are desired for the use as substrates and as device layers to take full advantage of the material properties.

Melt-based crystal growth methods are ill-suited for the growth of BN due to their inability to melt BN given its sublimation temperature of ~ 3000 °C. Gas phase approaches for the growth of BN have been demonstrated, though they are still dependent on the availability of existing seed crystals to grow upon, encouraging the pursuit of a true bulk crystal growth synthesis pathway.

Solution-based crystal growth approaches offer the most accessible path towards bulk BN growth. This talk will investigate the application of the ammonothermal method to the growth of BN. The ammonothermal method relies on the temperature-dependent dissolution of species, in this case BN, in a supercritical ammonia solution containing mineralizers to enhance solubility. Typical growth conditions occur at temperatures around 500-600 °C and pressures 150-250 MPa.

Building on prior studies evaluating the temperature-dependent solubility of BN in a sodium-containing supercritical ammonia solution,[1] this contribution will discuss the application of a temperature gradient across a baffled autoclave in this system for the first time. Both rhombohedral and hexagonal BN (rBN, and hBN, respectively) crystals were grown on the autoclave walls and on seed crystals of cubic BN (cBN) in the lower temperature, lower solubility zone of the autoclave.

The structure of the grown BN crystals is characterized via Raman spectroscopy, X-ray diffraction, transmission electron microscopy, selected area electron diffraction, and electron energy loss spectroscopy. An epitaxial relationship is identified for the preferential growth of rBN on the (111) cBN surface offering a pathway for bulk rBN growth.

[1] Dooley, J., et al. J. Cryst. Growth 621, 127381 (2023).

The authors acknowledge the support from NSF DMR under Award No. 1832824, Northrop Grumman, and the Lehigh New Faculty Startup Funds.

GR-Mon-B7 - Formation of layered polytypes during the thin film growth of boron nitride by chemical vapor deposition using boron trichloride as a boron source

1. Growth

Kazuhiko Hara[1]
Soma Ota[1], Ruki Aoike[1], Akira Takemura[1], Hayato Nakano[1], Hiroko Kominami[1], Kohei Shima[2], Shigefusa Chichibu[2]
[1] Research Institute of Electronics, Shizuoka University, 3-5-1 Johoku, Chuo-ku, Hamamatsu, 432-8011, Japan
[2] Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

Abstract text: Hexagonal BN (h-BN) has attracted much attention as a material for new electronics applications owing to its graphite-like crystal structure and wide bandgap (~ 6 eV). Among BN with layered crystal structures, h-BN is the most thermodynamically stable. However, the formation of rhombohedral BN (r-BN) has been reported in thin film growth using organic B sources [1]. We have grown BN films by chemical vapor deposition with BCl_3 and NH_3 as sources. The results have indicated the formation of several polytype, h-BN [2], r-BN [3] and Bernal BN (b-BN) [4] in our films. In this study, we investigated the factors to promote the formation of specific polytypes during film growth of BN.

The thin film samples were grown on c-plane sapphire. In our previous studies, N_2 has been used as a carrier gas. In addition, H_2 and Ar were used for the growth in this study.

The in-plane crystal orientation characterized by X-ray diffraction indicated that the films grown in N_2 and H_2 include both h-BN and r-BN for the growth at 1300 °C. However, the relative existence ratio of these polytypes depended on the growth atmosphere, with a higher ratio of h-BN in H_2. This difference was also reflected in the surface morphology; the film grown in N_2 consisted of well-aligned triangular grains whereas that grown in H_2 was dominated by hexagonal grains. Although the film grown in Ar did not show in-plane orientations, the triangular grains in the film suggested that the film is predominantly r-BN. A probable factor for the r-BN formation is C impurity [1]. Contrary to expectations from the carbon-free B source, detectable amounts of C were detected, with larger values for the films grown in N_2 and Ar than in H_2.

Despite the difference in crystallinity, these films showed an excitonic emission at 215 nm, which matches that of the h-BN powder. This result suggests that r-BN may also exhibit an exciton emission at approximately the same wavelength as h-BN at room temperature. More detailed evaluation of the origin of luminescence including b-BN will be presented.

This work was supported in part by JSPS KAKENHI (18K04231, 20K20993, 23K17757, 23K22786).

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GR-Mon-B8* - High-quality lattice-matched AlBN ferroelectric layers on SiC grown by rf reactive sputtering

1. Growth
Ken Shiraishi[1]
Tsunenobu Kimoto[1], Mitsuaki Kaneko[1]
[1] Department of Electronic Science and Engineering, Kyoto University, Nishikyo, Kyoto 615-8510, Japan

Abstract text: Nitride ferroelectric semiconductors have a high Curie temperature and attract attention as candidates for non-volatile memories operational at high temperature. Ferroelectric polarization in nitrides exists along the *c*-axis direction, and it is important to obtain high-quality and *c*-axis-oriented layers to achieve good ferroelectric properties (high E_c and large P_r). Among nitride ferroelectric semiconductors, aluminum boron nitride (AlBN) has recently been reported to exhibit ferroelectricity. Since AlBN at a B composition of approximately 5% is lattice-matched to silicon carbide (SiC) and SiC logic circuits can operate at high temperature, we consider AlBN/SiC heterostructure is the most promising system for achieving high-temperature ICs with non-volatile memory. In this study, AlBN layers were grown on SiC by rf reactive sputtering. The AlBN layer with a B composition of 4% achieved ω-scan full width at half maximum (FWHM) value of 0.9°, which is the lowest value ever reported for AlBN grown by sputtering as far as the authors know.

AlBN layers were grown on 4°-off SiC (0001) substrates by rf reactive sputtering using an alloy target of $Al_{0.95}B_{0.05}$ under various conditions of RF power and N_2 flow rates at 400°C. Pt and Al were deposited as the top and bottom electrodes, respectively. Polarization hysteresis was measured by triangular PUND measurements for the sample with a 75 nm-thick AlBN layer. The hysteresis loop was maintained from RT to 400°C.

The crystal orientation and B composition of the AlBN layers on SiC were investigated by XRD 2 θ-ω scans. It was confirmed that *c*-axis direction of the grown AlBN layers was tilted by 4° from the surface, meaning the inheritance of the substrate off-angle. 2θ-ω scan peak positions of the AlBN layers grown under different conditions located between 36.2° and 36.4° (different B composition). Assuming the Vegard's rule, the B composition of each sample was estimated to be from 3 to 5.5%.

The crystalline quality of the AlBN layers was analyzed by XRD ω-scan. The higher N_2 flow rate during the AlBN growth resulted in smaller FWHM values. From the relationship between the B composition and ω-scan FWHM values, smaller FWHM values were obtained from the AlBN layers of B composition about 4%. Comparing AlBN layers grown on Si or W in previous studies, the lowest FWHM value of 0.9° ever reported for the AlBN.

GR-Mon-B9 - First epitaxial growth of cubic boron scandium nitride (c-BScN)

1. Growth

Ryota Maeda[1]
Yoshitaka Taniyasu[1], Kazuhide Kumakura[1], Kazuyuki Hirama[1]
[1] NTT Basic Research Lab. NTT Corporation, Atsugi 243-0198, Japan

Abstract text: Cubic boron nitride (c-BN) has a wide bandgap of 6.3 eV, making it a promising material for high-power electronic devices [1]. We previously demonstrated the epitaxial growth of c-BN (111) layers on diamond (111) substrates using ion-beam-assisted molecular beam epitaxy and magnetron sputtering [2, 3]. The growth of c-BN-based alloys enables the development of electronic devices utilizing carrier confinement in heterostructures. In this work, we demonstrate the first epitaxial growth of c-BScN layers, an alloy of c-BN and cubic scandium nitride (c-ScN).

BScN layers were grown on diamond (111) substrates using a magnetron sputtering system with substrate biasing. Pyrolytic boron nitride and Sc served as sputtering targets, with the Sc target power varied from 0 to 105 W. Ar and N_2 gases were used and negative bias voltage was applied to the substrate stage to irradiate BScN with positive Ar and N plasma ions. A ~20-nm c-BN buffer layer was deposited on the diamond substrate before BScN growth.

First, we investigated the bias-voltage dependence of the growth phase at the Sc target power of 45 W. FT-IR absorption spectra revealed that at –110 V, both sp^3 and sp^2 bond absorption peaks were observed, indicating that a mixture of sp^3-bonded and sp^2-bonded phases are formed. In contrast, below –120 V, only the sp^3-related absorption peak was detected, indicating the formation of phase-pure BScN. From the X-ray diffraction measurement and cross-sectional TEM observations of the phase-pure BScN layer, we confirmed the epitaxial growth of a c-BScN (111) layer on the diamond (111) substrate. Sc atoms were uniformly incorporated, and the average Sc content was estimated to be 2% from the STEM-EDS mapping.

Next, we investigated the Sc target-power dependence of the BScN layers at the bias voltage of –140 V. Up to 75 W, the c-BScN layers were epitaxially grown, but above 90 W, the phase separation of BScN and ScN occurred. The Sc content increased with higher Sc target power: the Sc contents of c-BScN layers grown at 60 and 75 W were 6% and 16%, respectively, measured by STEM-EDS mapping.
The epitaxial growth of c-BScN layers will broaden the potential applications of c-BN-based high-power electronic devices.

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Heterostructures and implantation

2025-07-07
13:30 - 15:00
Heterostructures and implantation

PC-Mon-5* - Ultra-high-pressure annealing with a carbon capping layer for activation of Mg ion-implanted GaN

2. Physics and characterization

Kensuke Sumida[1]
Kacper Sierakowski[2], Tomasz Sochacki[2], Masahiro Horita[1], Michał Boćkowski[2], Tetsu Kachi[1], Jun Suda[1]
[1] Nagoya University, Nagoya, Aichi, Japan
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: To utilize Mg-ion implantation in the fabrication process of GaN power devices, it is essential to achieve sufficient activation of the implanted Mg with suppressing of thermal decomposition during post-implantation annealing. We demonstrated that ultra-high-pressure annealing (UHPA) can realize high Mg activation with suppressing thermal decomposition in Mg ion-implanted GaN [1, 2]. However, to achieve thermal equilibrium (Ga+1/2 N_2=GaN) near GaN surface during UHPA, GaN wafers should be covered by GaN powders. Utilization of GaN powders is not suitable for industrial applications due to low throughput, reproducibility and uniformity. In this study, we propose an alternative approach which uses a carbon capping layer (C-cap) instead of GaN powders on Mg-implanted GaN during UHPA.

Mg and N ions were implanted using multiple energies to form 600 nm box-profiles ([Mg]=[N]≅$10^{19}$$cm^{-3}$) into homoepitaxial n-type GaN (0001) layers. After formation of C-cap, UHPA was performed at 1300°C under 500 MPa of N_2 pressure for 60 or 120 min. After UHPA, the C-cap was removed by heat treatment in an oxygen atmosphere at 800 °C for 15 min. Successful removal of C-cap was confirmed by Auger electron spectroscopy (AES). Following the removal process, dehydrogenation annealing (800°C, 10 min, under a nitrogen atmosphere) and electrode formation (Ni/Au at four corners of the chip) were carried out for Hall-effect measurement.

Scanning electron microscopy (SEM) revealed that the GaN surface remained smooth and homogeneous after 120 min of UHPA and subsequent C-cap removal process. Hall-effect measurements showed the activation of implanted Mg atoms by UHPA with C-cap. The temperature dependence of carrier concentrations was comparable to that of previous results using UHPA with GaN powders [3]. These findings indicate that the combination of UHPA and C-Cap facilitates efficient Mg activation while suppressing thermal decomposition, contributing to improved yield and reducing costs in the annealing process.

This work was supported by MEXT-Program for Creation of Innovative Core Technology for Power Electronics Grant Number JPJ009777.

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PC-Mon-6 - Magnesium Intercalation in Gallium Nitride With Different Polarities

2. Physics and characterization
Jia Wang[1]
Hiroshi Amano[1]
[1] Institute for Advanced Research, Nagoya University, Japan and Institute of Materials and Systems for Sustainability, Nagoya University, Japan.

Abstract text: While intercalation phenomena are well explored in layered materials such as graphite, their occurrence in non-van der Waals (non-vdW) materials, such as wurtzite compounds, is scarcely observed. This work provides fresh insight into the field by demonstrating Mg intercalation in wurtzite GaN, extending our understanding of Mg behavior beyond interstitial incorporation and segregation. Through systematic investigation, a hierarchical relationship is established among Mg interstitials, Mg segregation, and the emergent intercalation phenomenon. We conclude that Mg interstitials tend to segregate into short, single-atomic-layer sheets, which, when closely spaced along [0001] (a few nm), lead to intercalation behavior. Specifically, atomic-resolution scanning transmission electron microscopy reveals that Mg intercalation induces two distinctive structural modifications: (i) periodic polarity inversion along [0001], and (ii) ultra-high uniaxial compression (up to tens of GPa) within confined GaN interlayers bounded by single-atomic Mg sheets.

We experimentally demonstrate polarity-dependent intercalation pathways through comparative studies of metal-polar, non-polar, and N-polar GaN substrates. Thermal annealing of metallic Mg on metal-polar and non-polar surfaces successfully induces intercalation, whereas equivalent treatment on N-polar GaN exhibits no intercalation. This polarity dichotomy may originate from contrasting diffusion kinetics: in metal-polar systems, the downward-pointing polarity inversion domains align with top-down Mg diffusion profiles, while N-polar exhibit upward-oriented domains that kinetically hinder Mg transport. On the other hand, we observed that Mg intercalation occurs in N-polar GaN through ion implantation of Mg ions.

Contrary to the well-established self-compensation mechanism in heavily Mg-doped GaN, where Mg segregation limits p-type conductivity, Mg-intercalated GaN exhibits enhanced charge densities and p-type conductivity. Specifically, we observe a significant increase in ionized acceptor concentrations in the space charge region of n-GaN and improved hole concentrations in p-GaN. These electronic modifications enable superior ohmic contacts (contact resistivity ~10^{-5} $\Omega \cdot cm^2$) for p-GaN. This work redefines intercalation physics in covalent semiconductors while providing practical solutions for III-nitride device engineering.

PC-Mon-7* - Determination of optical losses in AlGaN-based UVC multimode waveguides

2. Physics and characterization

Verena Kowallik[1]
Martin Guttmann[2], Bruno Marx[1], Vincent König[1], Tim Wernicke[1], Michael Kneissl[3]
[1] Technische Universität Berlin, Institute of Solid State Physics, Berlin 10623, Germany
[2] Ferdinand-Braun-Institut (FBH), Berlin 12489, Germany
[3] Technische Universität Berlin, Institute of Solid State Physics, Berlin 10623, Germany; Ferdinand-Braun-Institut (FBH), Berlin 12489, Germany

Abstract text: Photonic integrated circuits (PICs) enable the combination of various optical components and condense complex optical setups into square millimeter sized chips. This allows wafer-scale low cost fabrication as well as lower power consumption and higher robustness. Applications for PICs in the UV spectral range like sensing of gases in the air, chemicals in water or biomolecules as well as Raman spectroscopy require wide bandgap materials to ensure UV transparency. Currently, no ideal material has been identified that enables low loss waveguides and simultaneously the implementation of active and passive components, e.g., modulators, detectors and light emitters, in the UV wavelength range. One possible candidate is the AlGaN alloy system which is already successfully employed for the fabrication of UV light emitting diodes (UV-LEDs) and UV lasers. However, the optical properties of AlGaN materials, especially the absorption losses in AlGaN waveguides have not yet been studied in detail, especially not in the UVC spectral range below 280 nm. In this work, the absorption in 200 µm wide n-$Al_{0.76}Ga_{0.24}N$ waveguides grown on AlN/sapphire are investigated using UV-LEDs emitting at 262 nm and detectors of the same heterostructure. By varying the waveguide length between UV-LED and detector the optical losses can be determined using Beer-Lambert law. Using an integrated AlGaN photodiode, we were able to measure photocurrents as low as 1 nA and found that the photocurrent decreases exponentially with increasing waveguide length corresponding to an optical loss of (17±2) cm^{-1}. To analyze this result, Monte-Carlo ray-tracing simulations were performed and compared with experiment. We identified the absorption in the AlGaN waveguides as one contributing factor to the optical losses. In addition, propagation through the AlN base layers and scattering losses from surface roughness must be considered as well. In the presentation, we will discuss the impact of the absorption coefficient in the different layers. Also the influence of defect density and surface roughness are investigated by comparing devices grown on different AlN/sapphire template (planar, high temperature annealed (HTA), epitaxial lateral overgrown (ELO) and double growth annealed (DGA)) on the total losses using the simulation and measurement results of the investigated devices.

PC-Mon-8 - Impacts of ultra-high-pressure annealing on undoped and ion-implanted GaN studied by photoluminescence measurements

2. Physics and characterization

Kohei Shima[1]
Tetsuo Narita[2], Akira Uedono[3], Michal Bockowski[4], Jun Suda[5], Tetsu Kachi[6], Shigefusa Chichibu[1]
[1] Inst. Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai 980-8577, Japan
[2] Toyota Central R&D Labs., Inc., Nagakute, Aichi 480-1192, Japan
[3] Facult. Pure and Applied Science, University of Tsukuba, Tsukuba 305-8573, Japan
[4] Inst. High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142 Warsaw, Poland
[5] Dept. Electronics, Graduate School of Engineering, Nagoya University, Aichi 464-8603, Japan
[6] Inst. Materials and Systems for Sustainability, Nagoya University, Aichi 464-8601, Japan

Abstract text: To realize high-performance GaN power-switching devices, precise conductivity control via ion-implantation (I/I) is essential. However, Mg-I/I introduces high concentration (>10^{19} cm^{-3}) of $V_{Ga}V_N$ divacancies, which agglomerate into large clusters such as $(V_{Ga}V_N)_3$ after post-implantation annealing [1]. Because such vacancy clusters work as nonradiative recombination centers (NRCs) [2], minimizing their formation is essential. To comply, ultra-high-pressure annealing (UHPA) under 1-GPa-N_2 has emerged as a promising technique [3]. However, its effects on GaN surfaces and carrier recombination dynamics governed by midgap recombination centers (MGRCs) remain unclear. In this presentation, superiorities of UHPA for undoped, Si-implanted, Mg-implanted, and Mg/N-implanted GaN epilayers are presented by using PL and time-resolved PL measurements.

For undoped GaN, PL lifetimes at 300 K for the near-band-edge (NBE) emission decreased with increasing the annealing temperature (T_a) , indicating higher T_a increased the concentration of MGRCs. In contrast, for I/I-GaN, PL lifetimes or PL intensities at 300 K of the NBE emission increased with increasing T_a, indicating higher T_a decreased the concentration of MGRCs originating from the I/I-induced vacancy-type defects. Nevertheless, MGRC concentrations in I/I-GaN after UHPA remained several orders of magnitude higher than in undoped GaN. Additional N-I/I onto Mg-implanted GaN followed by UHPA at T_a = 1480 ºC enhanced the activation of Mg_{Ga} acceptors and decreased the concentration of MGRCs. For Mg- and Mg/N-implanted GaN, the progressive activation of Mg_{Ga} acceptors with increasing T_a was confirmed. However, the PL lifetimes for Mg- and Mg/N-implanted GaN with Mg concentrations higher than 1×10^{18} cm^{-3} were limited to shorter than 1 ps. To fabricate reliable p-contacts and electron inversion layers using Mg- or Mg/N-I/I combined with UHPA, it is crucial to eliminate residual defective layers near the surface.

This work was supported by MEXT-Program of R&D of Next-Generation Semiconductor (JPJ005357), Creation of Innovative Core Technology for Power Electronics (JPJ009777), JSPS KAKENHI (JP16H06427 and 21H01826), and the Polish National Science Center through Project No.2023/49/B/ST5/03319.

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PC-Mon-9 - Electromodulation spectroscopy of built-in electric fields in hybrid III-N heterostructures

2. Physics and characterization

Ewelina Zdanowicz[1]
[1] Wroclaw University of Science and Technology, Wroclaw, Poland

Abstract text: All currently proposed optoelectronic devices are multilayered, based on heterostructures with multiple interfaces. In this context, the famous phrase 'the interface is the device,' as stated by H. Kroemer in his Nobel Lecture, remains as relevant as ever. Band alignment at the interfaces governs device operation—specifically, the energy barrier influences carrier dynamics and dictates carrier extraction or injection, ultimately determining device performance. This underscores the crucial role of interface engineering in the development of efficient optoelectronic devices.

Today, III-N heterostructures serve as a reliable platform for tandem devices, incorporating emerging materials such as van der Waals crystals and perovskites. This integration has enabled the demonstration of solar cells, LEDs, transistors, and photodetectors.

In this talk, a methodology providing direct access to electronic phenomena at the interface in GaN-based hybrids will be described. It will be demonstrated that combining GaN structures with a controlled distribution of the built-in electric field and electromodulation spectroscopy—particularly contactless electroreflectance (CER)—is highly effective for studying carrier behavior at GaN surfaces and interfaces. Furthermore, CER will be shown to be a powerful tool for carrier tracking.

Radio Frequency Devices 3 (Enhanced Performance)

2025-07-07
15:30 - 17:00
Radio Frequency Devices 3 (Enhanced Performance)

ED-Mon-10* - Enhanced RF Performance of mmWave GaN HEMTs via Displacement Field Coupling with fMAX=430 GHz

4. Electronic devices

Hakan Cankat Gür[1]
Onder Soydal[1], Mohammad Rezaei[1], Utku Agtas[1], Elison Matioli[1]
[1] Power and Wide-Band-Gap Electronics Research Laboratory (POWERlab), Institute of Electrical and Micro Engineering, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Abstract text: Gallium Nitride (GaN) is the leading material system for high-frequency and high-power applications due its high saturation velocity (v_{sat} ~$2*10^7$ cm/s) and critical E-field (E_C ~ 3.3 MV/cm), playing a critical role in both defense industry and telecommunications. Despite its potential, GaN devices still operate below their theoretical limits, hindering their performance at mmWave range (particularly in the D-G band) [1]. Conventional scaling approaches [2] to enhance f_T and f_{MAX}—such as regrown contacts and extreme lateral scaling—introduce trade-offs, including reduced breakdown voltage (V_{BR}) and increased DC power dissipation, ultimately limiting GaN RF system efficiency and operating voltage.

In this work, we investigate a novel GaN transistor architecture that leverages strong RF coupling to achieve ultra-low access resistance, enhancing RF performance while maintaining high breakdown voltage. Unlike conventional designs, our approach utilizes displacement field coupling to separate DC and RF signal paths, enabling more efficient amplification. This separation reduces DC power dissipation while improving RF performance, and directly addressing the high-frequency operation-breakdown voltage trade-off. Unlike conventional devices, the unilateral gain U, and the current gain h_{21} do not decay by 20dB/decade, as access resistances improve with frequency. To account for this effect, a modified small-signal equivalent circuit model is developed, showing excellent fit with the measurements up to 50 GHz, which will be discussed in detail during the talk. The fabricated devices demonstrated excellent RF performance, achieving f_T /f_{MAX} of 170/430 GHz and 180/380 GHz, alongside a 2.5-fold improvement in static breakdown voltage. Additionally, the reduced DC quiescent current enhances amplification efficiency compared to conventional HEMTs. This talk will provide a detailed explanation of the proposed architecture, its impact on RF transistor performance, and its potential to enable high-performance, power-efficient GaN-based mmWave devices. By extending the LNA operating power range and improving PA efficiency, this architecture could pave the way for higher power and efficient RF devices.

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ED-Mon-11* - Impact of Gate Dielectric and Recess on Gate Modulation in Self-Aligned p-Channel GaN Transistors

4. Electronic devices

Joshua Park[1]
John Niroula[1], Jung-Han Hsia[1], Tomás Palacios[1]
[1] Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract text: Recent advances in the performance of gallium nitride (GaN) transistors have led to their widespread adoption in power switches and amplifiers. However, further circuit-level improvements are limited as the p-channel GaN FETs (p-FETs) performance significantly lags behind that of n-channel GaN FETs (n-FETs). The recessed gate p-FET significantly improves the on/off ratio and current density but requires optimization of the gate oxide and recess depth [1]. Understanding how these parameters impact the device performance is crucial in achieving the next generation of fully integrated, scalable GaN power circuits.

In this work, we fabricated long channel self-aligned GaN p-FETs (L_g=L_{sd}=2-6μm) to study the effect of gate recess depth and gate oxide deposition method on leakage and current density. Our devices were fabricated on a p-GaN/uid-GaN/AlN/AlGaN/GaN epitaxial structure. Using a Cl-based dry etch to fabricate devices of three different recess depths, we demonstrated that small increases in the gate recess near a critical recess depth considerably reduces the saturation drain current and shifts the threshold voltage positively. We also studied the differences between thermal atomic layer deposition (ALD) and plasma-enhanced ALD Al_2O_3 gate dielectrics on leakage and hysteresis. GaN p-FETs with thermal ALD Al_2O_3 gate dielectrics have nearly 10^4 times higher leakage in the high field reverse-bias regime compared to those with plasma-enhanced ALD Al_2O_3. Leakage measurements confirm this is due to reduced tunneling leakage in the gate dielectric. However, thermal ALD Al_2O_3 is more effective at passivating the plasma damage induced during the gate recess, resulting in less hysteresis than p-FETs with plasma-enhanced ALD Al_2O_3. To the best of the authors' knowledge, this is the first study on the impact of gate dielectrics on the hysteresis of GaN p-FETs. These findings improve our understanding of the material and design space of GaN p-FETs, serving as a foundation for further improvements in GaN p-FET technology.

References:

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Acknowledgements:

Device fabrication was conducted at MIT.nano. This work was sponsored in part by MIT Lincoln Laboratory, the Air Force Office of Scientific Research (AFOSR) under award no. FA9550-22-1-0367, and Lockheed Martin Corporation under award no. 025570-00036.

ED-Mon-12* - Origin of Local Barrier Height Lowering in AlN Schottky Barrier Diodes

4. Electronic devices

Issei Sasaki[1]
Masanobu Hiroki[2], Kazuyuki Hirama[2], Kazuhide Kumakura[2], Yoshitaka Taniyasu[2], Atsushi Tanaka[3], Yoshio Honda[3], Takuya Maeda[1]
[1] The University of Tokyo, Tokyo, Japan
[2] NTT Basic Research Laboratories, Kanagawa, Japan
[3] Nagoya University, Aichi, Japan

Abstract text: AlN is an attractive material for high voltage and high temperature electronic devices owing to its ultrawide bandgap and high breakdown field. Recently, we identified the two current transport in AlN Schottky barrier diodes (SBDs): the nearly ideal thermionic field emission [1] and the shoulder-like leakage caused by local barrier height lowering (LBHL) [2]. In this study, we investigated the origin of the LBHL by emission microscopy observation.

We fabricated AlN SBDs with a graded n^+-AlGaN top contact layer on both SiC and AlN substrates. The threading dislocation densities (TDDs) for the devices on SiC and AlN substrates are approximately 10^9 and 10^3 cm^{-2}, respectively. We performed the *I-V* measurements for circular Schottky electrodes with diameters of 200, 400 and 800 μm. For the 200 μm devices, 20–30% devices showed nearly ideal characteristics. On the other hand, the others showed the shoulder-like leakage. As the size increased, the proportion of the devices with nearly ideal characteristics decreased. From the relationship between the yield and the area, the density of the defects causing LBHL is estimated as ~3×10^3 cm^{-2} for devices on a SiC substrate. The similar trends were observed for the devices on an AlN substrate, and the density was estimated as ~4×10^3 cm^{-2}. The defect densities do not depend on the TDDs, and the defects seemed to be generated via the epitaxial growth.

The emission microscopy observation was conducted. An infrared light emission from heating region (leak spots) can be detected. The devices with nearly ideal characteristics emitted no detectable light, whereas those with shoulder-like leakage showed a dotted emission pattern. Under optimized measurement condition, we found that the emissions were aligned in a linear pattern with an opening angle of 120°.

Previously, X-ray topography for AlN bulk crystals was reported [3], and the basal plane dislocations (BPDs) oriented along the six <1-100> directions with an opening angle of 120° existed with the density of the order of 10^3 cm^{-2} [3]. The shape and the density are consistent with the defects observed in this study. These results strongly suggest that BPDs along <1-100> are predominantly responsible for LBHL in AlN SBDs.

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ED-Mon-13* - Comprehensive Study on Velocity-Field Characteristics of 2DEG in AlGaN/GaN Heterostructures

4. Electronic devices

Yusuke Wakamoto[1]
Takahiko Kawahara[2], Shigeki Yoshida[2], Kozo Makiyama[2], Ken Nakata[2], Takuya Maeda[1]
[1] The University of Tokyo
[2] Sumitomo Electric Industries, Ltd

Abstract text: In modeling the device properties of GaN HEMTs, detailed understanding of drift velocity of the 2DEG is essential. We have previously reported precise characterizations of the velocity-field characteristics of the 2DEG and its temperature dependence [1]. In this work, we fabricated test devices with varying 2DEG densities and comprehensively characterized the drift velocity under various density and temperature conditions.

We prepared three AlGaN (15 nm)/GaN heterostructures grown by MOVPE on semi-insulating SiC substrates. The Al compositions of the AlGaN barriers are 11%, 22%, and 32%. The regrown n^+-GaN was selectively formed to achieve good ohmic contacts. SiN_x was deposited by PECVD for passivation. Ti/Au metals were evaporated as ohmic contacts. The contact resistances, measured by TLM, were as low as 0.4-0.7 Ωmm. The 2DEG densities, obtained by Hall effect measurements, for Al compositions of 11%, 22%, and 32% were 2.7×10^{12} cm^{-2}, 8.1×10^{12} cm^{-2}, and 1.3×10^{13} cm^{-2}, respectively.

To obtain the velocity-field characteristics free from a self-heating effect, pulsed *I-V* measurements were performed on the TLM structures (width: 40–80 μm). Velocity saturation was observed, and the velocity-field curves were well fitted to the Caughey-Thomas model [2] under all conditions. At room temperature, the saturation velocity increases as 2DEG density decreases, despite similar low-field mobility. We obtained the density-dependent model of the saturation velocity approximately 10–30% higher than the previous work [3], possibly due to the suppression of current collapse and/or surface depletion. At a low sheet density of 2.7×10^{12} cm^{-2}, the saturation velocity almost linearly decreased from 25 K to 573 K. On the other hand, at higher sheet densities, the saturation velocity was almost constant from 25 K to 250 K then linearly decreased at high temperatures, which is well explained by the Hirakawa-Sakaki model [4]. The difference may be related to the change in degenerate electron states with the threshold density of 3.8×10^{12} cm^{-2}, as described in a previous study [5]. This study is very useful for improving the design of GaN HEMTs.

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ED-Mon-14* - Processing and Characterization of N-polar GaN/AlGaN Heterostructure Field-Effect Transistors Grown on 200 mm Sapphire Substrates

4. Electronic devices

Liubou Padzialioshkina[1]
Arno Kirchbrücher[1], Qi Shu[1], Christof Mauder[2], Robert Oligschläger[2], Michael Heuken[3], Holger Kalisch[1], Andrei Vescan[1]
[1] Compound Semiconductor Technology (CST), RWTH Aachen University, Aachen, Germany
[2] AIXTRON SE, Herzogenrath, Germany
[3] Compound Semiconductor Technology (CST), RWTH Aachen University, Aachen, Germany; AIXTRON SE, Herzogenrath, Germany

Abstract text: N-polar GaN has been attracting growing attention due to a number of theoretically expected advantages over conventional Ga-polar GaN in heterostructure field-effect transistors (HFETs). These advantages include improved contact resistance, superior carrier confinement, reduced buffer leakage currents, advanced scaling. In this work, N-polar GaN/AlGaN heterostructures grown on 8" sapphire wafers are characterized, and test HFETs are fabricated. Material deposition is carried out in a commercial MOCVD tool (AIXTRON G5+C 5×200 mm Planetary Reactor). Wafers with identical stacks except for the top uid-GaN channel with different thicknesses (15, 25 and 35 nm) are investigated.

Prior to HFET fabrication, the wafers are evaluated with X-ray diffraction and photoluminescence measurements to study composition (AlGaN barrier with 27 % Al), crystal quality (283 arcsec FWHM of (0002) GaN plane), and with atomic force microscopy for surface roughness (RMS of 6.7 nm for a 5×5 μm^2 area). Next, HFETs are realized starting with Ti/Al/Ni/Au ohmic contacts fabricated using a combination of optical lithography, electron-beam evaporation, lift-off, and annealing. For electrical isolation, inductively-coupled plasma reactive ion-etching and ion implantation are compared in their effectiveness to suppress device-to-device and device-to-buffer leakage, as well as their impact on the resulting HFET performance. After isolation, Ni/Au gates (down to 1 µm length) are deposited similarly. HFET fabrication completes with a SiN_x passivation layer deposited with a plasma-enhanced CVD tool.

Ohmic contacts with low contact resistance of 0.5 Ohm·mm are achieved, and the Au/Ni/GaN Schottky contacts yield a barrier height of 0.55 eV. The heterostructures demonstrate high sheet carrier concentration in a two-dimensional electron gas of 10^{13} cm^{-2} with moderate mobility of 800 cm^2/Vs resulting in transistor currents up to 500 mA/mm without passivation.

HFETs without passivation, with passivation-first (prior to gate processing) and passivation-last (after gate processing) are evaluated with pulsed current-voltage measurements to investigate surface-related trapping effects. Although introducing passivation results in elevated leakage currents, notably reduced DC-RF dispersion was observed (2.5% gate lag collapse at knee voltage after passivation compared to 95% collapse before passivation).

Red LEDs

2025-07-07
15:30 - 17:00
Red LEDs

OD-Mon-10 - Radiative and non-radiative recombination mechanisms in red-emitting InGaN quantum wells

3. Optical devices

Yoichi Kawakami[1]
Zhaozong Zhang[1], Ryota Ishii[1], Mitsuru Fnato[1], Daisuke IIda[2], Kazuhiro Ohkawa[2]
[1] Kyoto University, Department of Electronic Science and Engineering, Kyoto, Japan
[2] KAUST, CEMSE Division, Thuwal, Saudi Arabia

Abstract text: Intensive research on InGaN-based LEDs has brought the external quantum efficiency of blue LEDs close to the physical limit of 100%, and the efficiency of green LEDs has also improved markedly in recent years. However, the efficiency in the red region remains at a low level. Our group has assessed radiative and non-radiative recombination processes in red-emitting InGaN QWs at macro-, micro-, and nano-level spatial resolutions.

The sample is a hybrid InGaN QW structure, which consists of a red-emitting single QW (SQW) stacked on top of a blue-emitting SQW. The internal quantum efficiency (IQE), radiative recombination lifetime (τrad), and non-radiative recombination lifetime (τnrad) were evaluated at room temperature by selectively photoexciting only the red emitting SQWs at 515 nm. As a result, we found that IQE increases with increasing optical excitation intensity, and obtained IQE =5.9% under relatively strong excitation. Furthermore, τrad =10μs and τnrad =100ns under weak excitation, but τrad =1μs and τnrad =50ns under strong excitation. This indicates that under weak excitation, the radiative recombination lifetime is very long due to the quantum confined Stark effects, whereas the 10-fold faster radiative recombination lifetime under strong excitation is mainly due to the screening effect of the internal electric field. The dependence of the non-radiative recombination lifetime on the photoexcitation intensity is not so large, indicating that the Auger-Meitner effect plays a minor role.

Next, photoluminescence (PL) mapping by confocal and scanning near-field optical microscopy (SNOM) shows that regions of weak red emission are strongly correlated with dark regions of underlying blue emission, and parasitic green emission is always observed in the regions of significantly dark red emission. Our correlative SNOM and atomic force microscopy (AFM) reveals that the green emission originates from trench defects with In segregation. Therefore, trench defects with In segregation are one of the origins of the low IQE in red InGaN. The comparative X-ray diffraction and AFM analyses suggest that screw threading dislocations must be one of the triggers in the formation of trench defects. We believe that these findings will be useful for increasing the efficiency of future red-emitting InGaN-based LEDs.

OD-Mon-11 - High Efficiency, Narrow Linewidth, High Color Purity Red Micro-LEDs

3. Optical devices

Yuanpeng Wu[1]
Yixin Xiao[1], **Zetian Mi**[1]
[1] University of Michigan, Ann Arbor

Abstract text: To date, red-emitting InGaN micro-LEDs face critical challenges, including low external quantum efficiency (EQE) and poor color purity, primarily due to defects, dislocations, and broad emission linewidths in high-indium-composition quantum wells. In this work, we present a transformative approach to address these limitations by utilizing a nanowire photonic crystal (PhC) structure to significantly enhance the performance of red-emitting InGaN micro-LEDs. By coupling the spontaneous emission of the InGaN/GaN active region to the photonic band edge mode of the PhC, we achieved pure red emission with a narrow linewidth of ~5 nm, a remarkable improvement over the typical 40–90 nm linewidths observed in conventional devices. Importantly, the emission wavelength remained stable over a wide range of injection currents, eliminating the color shift commonly caused by the quantum-confined Stark effect (QCSE).

The optimized device demonstrated a record EQE of 12%, the highest reported for micrometer-scale red InGaN micro-LEDs, and a chromaticity coordinate of (0.67, 0.33), aligning precisely with the primary red color in the NTSC standard. This achievement highlights the potential for achieving high color purity and stability, which are essential for wide color gamut displays. Furthermore, the PhC structure enabled highly directional emission with a divergence angle of less than 15°, significantly improving light extraction efficiency. Detailed characterization revealed that the EQE and color stability were strongly influenced by the thickness of the Al_2O_3 passivation layer. Angular-resolved electroluminescence measurements confirmed the vertical emission mechanism, attributed to the coupling of lightwave along the Γ-K directions of the PhC.

The realization of high efficiency red-emitting InGaN micro-LEDs pave the way for monolithic integration of GaN-based RGB micro-LEDs with CMOS-driven circuitry. The demonstrated high efficiency, narrow linewidth, and excellent color stability underscore the potential of this approach for next-generation micro-LED displays with superior color rendering, high contrast ratios, and energy efficiency.

OD-Mon-12* - Efficient and Spectrally Stable c-Plane Red III-Nitride Light Emitting Diodes

3. Optical devices

Vincent Rienzi[1]
Alejandro Quevedo[1], Tanay Tak[1], Hsun-Ming Chang[1], Panpan Li[1], Matthew Wong[1], Kent Nitta[1], Stacia Keller[1], Michael Iza[1], Steven DenBaars[1], James Speck[1], Shuji Nakamura[1]
[1] University of California, Santa Barbara, Santa Barbara, USA

Abstract text: Color stability is a major challenge in long wavelength III-N light emitting diodes (LEDs), particularly for microLED based displays. As current density increases, a monotonic decrease in peak wavelength is observed and the LED blueshifts. In this work, we demonstrate high external quantum efficiency (EQE) red LEDs with negligible blueshift from 0.01 A/cm^2 to 100 A/cm^2.

Two LED wafers were grown in a metalorganic chemical vapor deposition reactor. Wafers 1 and 2 had 2.3 nm and 1.8 nm thick QWs, respectively. The LEDs were electrically probed on-wafer from 0.01 to 100 A/cm^2. For wafer 1, from 0.01 to 1 A/cm^2, the peak wavelength redshifted from 611 nm to 626 nm, remained 626 nm until 2.5 A/cm^2, and finally blueshifted to 608 nm at 100 A/cm^2. This corresponds to only a 3 nm net blueshift from 0.01 A/cm^2 to 100 A/cm^2 and an 18 nm blueshift from the LED's longest peak wavelength at 2.5 A/cm^2 to 100 A/cm^2. Wafer 2 demonstrated similar optoelectronic behavior, with the peak wavelength being stable from 0.01 to 0.5 A/cm^2 at 590 nm, redshifting to 601 nm by 2 A/cm^2, remaining there until 5 A/cm^2, and blueshifting to 590 nm at 100 A/cm^2. This corresponds to 0 nm net blueshift from 0.01 to 100 A/cm^2, and only an 11 nm blueshift from the LEDs longest wavelength at 5 to 100 A/cm^2. Wafer 1 was packaged in transparent encapsulant and tested in an integrating sphere. At 1.75 A/cm^2, an LED had a peak wavelength of 627 nm, corresponding to a peak wall-plug efficiency (WPE) of 4.8% and peak EQE of 7.5%.

This optoelectronic behavior is noteworthy because most blueshifting normally occurs at low current density, which is when our LEDs are redshifting. Additionally, our LEDS are at their highest efficiency when most optically red. A peak wavelength redshift was observed with increasing current density for III-nitride LEDs for the first time, leading to enhanced color stability in our LEDs compared to other red LEDs. This work is supported by the Solid State Lighting and Energy Electronics Center (SSLEEC), the Korean Institute for Advancement of Technology (KIAT), and Department of Energy Award # DE-EE0009691.

OD-Mon-13 - Pyramidal microLEDs Delivering RGB in Single Materials Systems

3. Optical devices

Lisa Rullik[1]
Ivan Martinovic[1], Chih-Wei Hsu[1], Andrei Vorobiev[1], Per Olof Holtz[1]
[1] Polar Light Technologies

Abstract text: Polar Light Technologies has developed a novel microLED technology that produces native RGB emission within a single materials system. The approach leverages a unique bottom-up fabrication method based on hexagonal GaN pyramids with InGaN quantum wells (QWs), enabling native emission of blue, green, and red light at 470 nm, 520 nm, and 625 nm respectively—without needing separate phosphor or quantum dot conversion layers.

Traditional microLED fabrication typically involves a top-down etching process of 2D quantum well structures. However, this method can introduce significant surface and sidewall damage, especially as device dimensions shrink, which increases non-radiative recombination and reduces external quantum efficiency (EQE). In contrast, the bottom-up strategy employed by Polar Light Technologies forms pyramidal structures that inherently avoid these issues. PLT's microLEDs offer benefits such as sub-Lambertian emission, making them highly suitable for applications requiring high pixel densities, like AR/VR displays and micro-projectors.

The selective area growth of GaN pyramids is achieved through Metal Organic Chemical Vapor Deposition (MOCVD) on SiN-masked GaN/SiC templates. The adaptability in the mask design ensures compatibility with commercial CMOS backplanes. The InGaN QWs grown atop these pyramids have tunable indium content, which is the key parameter for setting the emission wavelength. This single materials system not only streamlines manufacturing but also enhances integration with CMOS backplanes and ensures mechanical and thermal compatibility, paving the way to improved device longevity and color stability.

Additionally, the research identifies and addresses leakage current issues—a common limitation in microLED performance—by optimizing defect characterization, material composition, and interface engineering. These targeted improvements reduce leakage pathways, thus boosting efficiency and overall performance stability.

In summary, this innovative bottom-up approach for fabricating microLEDs enables the creation of high-performance R/G/B devices and opening a path to monolithic RGB devices and making them an ideal candidate for next-generation display technologies, especially in AR/VR applications.

OD-Mon-14 - High-temperature performance of InGaN-based red micro-light-emitting diodes using an epitaxial tunnel junction contact

3. Optical devices

Yimeng Sang[1]
Zhe Zhuang[2], Kun Xing[3], Feifan Xu[4], Rong Zhang[5], Bin Liu[4]
[1] School of Integrated Circuits, Nanjing University, Suzhou, 215163, China; School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China
[2] School of Integrated Circuits, Nanjing University, Suzhou, 215163, China
[3] School of Microelectronics, Hefei University of Technology, 193 Tunxi Road, Hefei 230009, China 4 Xiamen University, Xiamen 361005, China
[4] School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China
[5] Xiamen University, Xiamen 361005, China

Abstract text: Full-color micro-light-emitting diodes (μLEDs) are considered promising for next-generation display applications. While significant progress has been made in the development of efficient blue and green LEDs, achieving high-performance red emission remains a considerable challenge. AlGaInP-based red LEDs are highly desirable due to their excellent efficiency and optical properties. However, their development is hindered by issues such as high surface recombination velocity, long minority carrier diffusion lengths and severe thermal droop limit their development. In contrast, InGaN-based red μLEDs have emerged as a promising alternative due to their superior thermal robustness and reduced size effects. However, the epitaxial growth of high-efficiency InGaN-based red μLEDs remain challenging for the substantial internal stress in the quantum wells. Additionally, while several groups have demonstrated that InGaN-based LEDs with tunnel junction (TJ) contacts offer the advantages of improved current spreading and reduced optical loss, the impact of temperature on the performance of TJ contact at elevated temperatures has yet to be explored.

In this work, we employed MBE for the regrowth of a TJ on MOCVD-grown red μLED wafers, serving as a current spreading layer. The TJ-μLEDs achieved a high wall-plug efficiency (WPE) of 4.3% at 1 A/cm^2. The electrical efficiency at room temperature reached approximately 0.935, demonstrating excellent current spreading performance of the epitaxial tunnel junction. The current injection of the TJ-μLEDs could be further improved at elevated temperatures.

Notably, the redshift coefficient, which quantifies the temperature-dependent peak wavelength shift, was as low as 0.05 nm/K. Additionally, the high-temperature-to-room-temperature EL intensity ratio remained above 0.56, even at a low current density of 0.5 A/cm^2 at temperatures up to 80℃. These results highlight the superior high-temperature performance for our high-indium content TJ-μLEDs. Our findings provide valuable insight into the thermal droop behavior of the red TJ-μLEDs at low current densities, paving the way for developing efficient and temperature-tolerated red μLEDs in the future.

Bulk AlN

2025-07-07
15:30 - 17:00
Bulk AlN

GR-Mon-A6 - The development and characterization of 100 mm AlN semiconductor substrates

1. Growth

Robert T. Bondokov[1]
Kasey Hogan[1], Griffin Q. Norbury[1], Shogen Matsumoto[2], Connor G. Carr[1], Andrew A. Allerman[3], Andrew Armstrong[3], Brianna Klein[3], James Grandusky[1]
[1] Crystal IS, Inc., Green Island, NY, 12183, USA
[2] Asahi Kasei Corporation, Fuji 416-8501, Japan
[3] Sandia National Laboratories, Albuquerque, New Mexico 87123, USA

Abstract text: Ultra-wide bandgap semiconductor materials hold great promise for various commercial applications including radio frequency, power and optical devices which require high power density, high voltage and high voltage blocking capability. Aluminum nitride (AlN) substrates offer a compelling platform for these devices due to their high thermal conductivity, ultra-wide bandgap, and close lattice matching with other III-Nitrides. To evaluate this potential and to ensure practical commercialization, substrates with at least 100 mm in diameter are needed. In this work we report our approach to develop the 100 mm AlN single-crystal substrates including crystal growth and subsequent substrate preparation.

AlN single crystals are grown using PVT. Several crystal generations are used to expand the diameter from 2-inch seeds to crystals with diameters larger than 100 mm. The crystals are then ground, oriented, and sliced into wafers which are subsequently polished to obtain epi-ready surfaces. We report on achieving 100 mm substrates with useable area > 99% estimated using high-resolution cross-polar imaging. Furthermore, the quality of the substrates is evaluated using double-crystal XRD rocking curves and show FWHM of less than 30 arcseconds for both symmetric and asymmetric rocking curves. The EPD was obtained using standard eutectic melt and falls in the range $10^4 – 10^5$ cm^{-2}. The 100 mm AlN demonstrates high-purity with impurity concentrations of < 10^{17} cm^{-3} measured using SIMS. We demonstrate 100 mm AlN single-crystal substrates having room temperature thermal conductivity of ~ 295 W/m*K. Developing a consistent epitaxial process and device fabrication is critical for power electronics device applications. The ability to link these processes to substrate properties and resulting device performance will enable development of a standard semiconductor AlN substrate specification.

A 100 mm AlN substrate was used to grow a $Al_{0.85}Ga_{0.15}N/Al_{0.70}Ga_{0.30}N$ a HEMT structure by MOCVD. The epitaxial growth conditions were developed on 2” AlN substrates and transferred directly to the 100 mm AlN substrate. XRD and CV measurements were utilized to verify the structure and compare compositions and thickness values between the different size substrates. These results demonstrate the suitability of the 100 mm AlN substrates for developing next generation power electronics.

GR-Mon-A7 - Broad Characterization of Bulk AlN Substrates and Propagation into Epi Properties

1. Growth

Alan Jacobs[1]
Katie R. Gann[1], Emma Rocco[1], Nadeemullah Mahadik[1], Jaime Freitas[1], James Culbertson[1], Jeffrey Woodward[1], James Gallagher[1], Kasey Hogan[2], James Grandusky[2], Robert Bondokov[2], Michael Mastro[1]
[1] US Naval Research Lab, Washington, DC, USA
[2] Crystal Is, Inc., Green Island, NY, USA

Abstract text: The successful implementation of nitride semiconductors has led to an evolution in power and RF devices, as well as significant utilization of nitride emitters and detectors. Aluminum nitride (AlN) has garnered significant interest and importance as both a substrate material and an active semiconductor for advanced devices. The superior properties of AlN include a high thermal conductivity, an ultra-wide bandgap of 6.1eV resulting in an extreme breakdown field, and recently demonstrated doping capability. With the recent advent of large area native substrates, a knowledge gap remains on both large area wafer characteristics and propagation of properties and defects into epitaxial layers.

Here, AlN single crystal boules were grown using physical vapor transport (PVT) and then ground, oriented, and sliced into wafers which are subsequently polished to obtain epi-ready surfaces. Here we report on commercialized 50mm substrates characterized pre- and post- epitaxial growth of AlN. The substrates exhibit an overall high UV transmission indicating a low density of optically active defects. Surface morphology show low bow/warp with a smooth epi-ready surface and low roughness. Notably, a slight increase in roughness is observed in a six-fold symmetric pattern aligned crystallographically to the major flat. Photoluminescence, excited by sub-gap 325nm light, exhibits both radial symmetric and six-fold symmetric patterns indicative of some optically active mid-gap defect inhomogeneity consistent with visible wafer characteristics. Raman spectroscopy (488nm) confirms the overall high crystallographic quality expected of bulk PVT material with small spatial perturbations in near surface scattering intensity (~5μm measurement depth). Despite variation in the scatter intensity, peak position and full width at half maximum remain consistent (E_2^H = 655.68±0.06 cm^{-1}, A_1(LO) = 887.31±0.06 cm^{-1}) and narrow (3.53±0.06 cm^{-1} and 8.93±0.22 cm^{-1} respectively) over 2.28 cm^2 area maps indicating minimal stress and phonon dispersion variation within the crystal. Discussion will further include X-ray Topography, high resolution XRD mapping, cathodoluminescence mapping, and evolution of these characteristics with epitaxial growth.

GR-Mon-A8* - Al0.15Ga0.85N compliant microdisks: an innovative template unlocking AlGaN growth across the entire aluminium composition range

1. Growth

Lea Lacomblez[1]
Maud Nemoz[1], Sebastien Chenot[1], Blandine Alloing[1], Benjamin Damilano[1], Pierre-Marie Coulon[1]
[1] Université Côte d'Azur, CNRS, CRHEA, Valbonne, France

Abstract text: The diversity of applications for UV LEDs including UV curing, optical communication and disinfection, necessitates the use of an AlGaN buffer layer with the ad-hoc Al composition to enable the growth of high-quality quantum wells covering a broad wavelength spectrum, from UVA to UVC. Various template can be used to meet these requirements (e.g. GaN/Al_2O_3, AlN/Al_2O_3, bulk AlN); however none have been successfully exploited across the entire Al composition range due to strain and defect formation resulting from lattice mismatch.

The goal of this study is to demonstrate the potential of our innovative AlGaN microdisk platform to grow AlGaN buffer layers with Al composition ranging from 0% to 100%.

We first grow a thin ≈ 80 nm $Al_{0.15}Ga_{0.85}N$ layer on 2'' GaN/Al_2O_3 wafer by metal organic vapor phase epitaxy (MOVPE). We then create $Al_{0.15}Ga_{0.85}N/GaN$ micropillars by optical lithography and dry etching. Finally, we use selective thermal etching of GaN to obtain an $Al_{0.15}Ga_{0.85}N$ microdisk supported by a GaN pillar.

We investigated the MOVPE growth of AlGaN layers with various compositions on different templates: $Al_{0.15}Ga_{0.85}N$ microdisks, $Al_{0.15}Ga_{0.85}N/GaN$ micropillars, GaN/Al_2O_3 and AlN/Al_2O_3. Optical and scanning electron microscope images reveal the absence of defect such as pits or cracks when AlGaN regrowth is performed on $Al_{0.15}Ga_{0.85}N$ microdisks, regardless of the Al%. In contrast, pits and cracks appear on GaN/Al_2O_3 for all explored Al compositions, while they only start to manifest at higher Al% (>60%) on $Al_{0.15}Ga_{0.85}N/GaN$ micropillars. Atomic force microscopy measurements were used to monitor the surface roughness and estimate the threading dislocation density (TDD). AlGaN growth on microdisks resulted in a smooth surface and a TDD in the mid-10^8 cm^{-2} up to 50% Al. X-Ray Diffraction experiments revealed that the $Al_{0.15}Ga_{0.85}N$ microdisk can deform and accommodate more strain induced by regrowth than the $Al_{0.15}Ga_{0.85}N/GaN$ micropillar, which explains the absence of cracks and pits even at high Al%. Finally, room temperature cathodoluminescence showed clear near band edge emissions from the various AlGaN regrowth on AlGaN microdisks, ranging from 310 nm to 204 nm.

As a result, $Al_{0.15}Ga_{0.85}N$ microdisks appear as a highly compliant platform that show great potential for the growth of AlGaN-based LED structures spanning from UVA to far-UVC.

GR-Mon-A9 - Efficient Diameter Enlargement of Bulk AlN

1. Growth

Carsten Hartmann[1]
Lutz Kirste[2], Merve Kabukcuoglu[3], Carsten Richter[1], Matthias Bickermann[1], **Thomas Straubinger**[1]
[1] Leibniz-Institut für Kristallzüchtung (IKZ), Max-Born-Str. 2, Berlin, Germany
[2] Fraunhofer Institute for Applied Solid State Physics (IAF), Freiburg, Germany
[3] Institute for Photon Science and Synchrotron Radiation (IPS), KIT, Karlsruhe, Germany

Abstract text: The ultra-wide band gap semiconductor AlN, as well as the ternary AlGaN alloy, have a number of attributes that make this material system promising for electronic and optoelectronic devices. Leveraging their extremely wide bandgap, Al(Ga)N enables the production of LEDs emitting deep into the far ultraviolet C (UVC) spectrum. In addition to their potential in deep-UV photonics, devices based on AlN present compelling prospects for the advancement of next generation high-frequency power conversion. Notably, AlN-based high-power transistors have the potential to outperform those made from the two most common wide bandgap semiconductors, SiC and GaN.

To fully exploit the potential of the Al(Ga)N system, high-quality native AlN substrates with industrially relevant diameters are required. In recent years, the growth of bulk AlN crystals by Physical Vapor Transport (PVT) has advanced significantly, laying the foundation for substantial improvements in device performance. But typically, diameter expansion is very limited, necessitating many crystal generations to achieve efficiently usable diameters ≥ 2 inches.

Our team introduced an approach that overcomes this restriction with a new seed holder design, enabling free crystal growth without parasitic grain contact [1]. This allows precise adjustment of the radial temperature gradient and significantly increasing lateral growth rates. At a seed temperature of 2230 °C, growth rates reach approximately 200 µm/h in both the N-polar and prismatic m directions, resulting in huge expansion angles of around 45° along the entire crystal length. The crystal length is currently 5-7 mm, with a diameter increase of approximately 10-12 mm in each crystal generation. First 2 Inch AlN crystals could be grown recently.

X-ray topography (XRT) measurements on chemo-mechanically polished c-plane and m-plane AlN wafers were used to identify the lateral dislocation distribution and its evolution, respectively. We found an inhomogeneous distribution with regions that are more or less dislocation-free along the [11-20] directions. In contrast, regions along the [1-100] directions exhibit dislocation densities of approximately 1-5x10^3/cm². Both types of regions expand radially in a self-similar manner during crystal growth.

References

[1] C. Hartmann et al., APEX 16, 075502 (2023).

GR-Mon-A10 - Improving the quality of PVT-grown AlN-crystals by utilizing a seed recovery process

1. Growth

Sven Besendörfer[1]
Gleb Lukin[1], Roland Weingärtner[1], Leon Schiller[1], Jochen Friedrich[1]
[1] Fraunhofer Institute for Integrated Systems and Device Technology IISB

Abstract text: Aluminum nitride (AlN) is a raising material for future high frequency and power electronics applications due to its high thermal conductivity of 3-4 W/cmK and its ultra-wide bandgap of 6.2 eV resulting in an extremely high critical electrical field and energy efficiency of AlN-based transistors. However, diameters of at least 100 mm are needed to arouse industrial interest in manufacturing electronic devices based on single crystal AlN-substrates. Strong efforts are being made to expand the diameter as effective as possible, but still many crystal generations are needed. This increases the probability that the crystal quality will degrade due to the successive incorporation of defects.
In this contribution we present a method of using seeds from minor quality crystals to grow crystals that are structurally of superior quality. This is achieved by combining a floating seed approach to grow AlN-crystals by physical vapor transport with a tailored seed preparation. The spatial defect distribution in terms of threading dislocations and basal plane dislocations obtained from X-ray topography measurements on seed wafers is compared to those on the grown AlN-crystals. It is shown that extended defects such as threading dislocation clusters or polycrystalline inclusions in the seed can be eliminated entirely. The corresponding regions of the grown crystals show a near-zero density of threading dislocations, especially of those with a screw component. However, a tendency to increased amounts of basal plane dislocations is observed. The consequences of such defect transformation for the structural quality of a subsequent crystal generation are presented. Our results suggest an opportunity for seed recovery by the rapid growth of new, high-quality material after removal of defective portions of the seed. The method is very relevant in terms of being able to maintain very good structural quality even over a large amount of crystal generations.

GaN substrates - growth and processing

2025-07-07
15:30 - 17:00
GaN substrates - growth and processing

GR-Mon-B10 - Impact of Dopants on the Mechanical Properties and Wafering Behavior of GaN substrates.

1. Growth

Takafumi Odani[1]
Kenta Tate[1], Takehiro Yoshida[1], Satoru Izumisawa[1]
[1] Mitsubishi Chemical Corporation, Ushiku, Ibaraki, Japan

Abstract text: GaN exhibits significant changes in fragility, hardness, and other mechanical properties when doped with various elements. These changes in mechanical properties substantially influence the behavior of GaN substrates during wafering. It is important to study the critical role of dopants in the mechanical characteristics of GaN crystals, which is a crucial factor in addressing the cost reduction challenges associated with GaN substrates manufacturing. We have grown Fe-, C- and Mn-doped GaN crystals by hydride vapor phase epitaxy (HVPE) with the doping concentration between 1×10^{18} and 5×10^{18} cm^{-3} and investigated the mechanical properties of semi-insulating GaN substrates. Bulk GaN substrates used as seeds for the growth had threading dislocation densities between 5×10^{5} and 1×10^{6} cm^{-2}.

The Ga surfaces of the doped GaN crystals were rough-ground to achieve flatness and subsequently mirror-ground using #7000 grindstones in separate batches, using an unintentionally doped (UID) GaN crystal as a reference. Fe- and C-doped GaN were ground with a pressure of 24.5 kPa, while Mn-doped GaN was ground with a pressure of 44.1 kPa.

The ratio R defined by the mass of the crystal removed to that of the grindstone consumed, was calculated to discuss the grinding behavior among the different dopants. The R values for Fe-, C-, and Mn-doped GaN crystals were found to be 2.6, 0.86, and 2.1 times that of the UID substrate, respectively. It was demonstrated that the grinding behavior varies significantly depending on the dopant.

In our presentation, we will discuss fundamental physical properties such as Vickers hardness, along with practical processing data like wafering rates. This comprehensive analysis aims to provide valuable insights for optimizing GaN substrate wafering processes.

GR-Mon-B11 - In situ TBCl Etching: A Robust Strategy toward Defect-Free GaN Regrowth Interfaces

1. Growth

Haoran Qie[1]
Yaozong Zhong[1], Xiaolu Guo[1], Tengfei Li[1], Hongwei Gao[1], Xinchen Ge[1], Fangqing Li[1], Qian Sun[1]
[1] Key Lab of Semiconductor Display Materials and Chips, Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences

Abstract text: GaN regrowth plays a critical role in developing high-voltage and high-reliability electronic devices including junction field-effect transistors (JFETs), current aperture vertical electron transistors (CAVETs). This approach effectively circumvents the severe lattice damage and process incompatibility issues inherent in conventional ion implantation techniques. However, dry-etching damage and silicon contamination at the regrowth interface significantly degrade device performance by increasing leakage current and reducing breakdown voltage. While wet chemical cleaning methods demonstrate limitations in addressing etching damage and eliminating interfacial silicon contamination, especially when silicon contamination primarily originates from the atmosphere, it becomes imperative to develop *in situ* silicon removal and dry etching damage repair protocols within MOCVD systems.

In this study, we implemented tertiarybutylchloride (TBCl) as an *in situ* etchant for GaN surface treatment prior to Ga(Al)N regrowth via MOCVD. Through the synergistic combination of TBCl etching and wet cleaning, the interface silicon contamination sheet density was significantly reduced to 4.9×10^{11} cm^{-2}, with a corresponding peak concentration of 2.7×10^{17} cm^{-3}. Based on this foundation, we fabricated PiN diodes by combining p-GaN regrowth on a 1.5-μm-thick drift template with a dislocation density of approximately 1×10^{9} cm^{-2}. Under these conditions, the devices exhibit breakdown voltages exceeding 350 V, much higher than 210 V of the control device without TBCl etching, demonstrating the effective removal of silicon impurities at the interface.

To repair dry-etching damage, we initially adjusted the TBC1 etching conditions, successfully achieving the decomposition of the step-flow mode in GaN templates subjected to dry etching. Following the removal of the 90 nm etching damage layer using TBCl, the near-band-edge photoluminescence intensity of the sample exhibited a 12-fold enhancement. Concurrently, surface roughness of the sample was only 0.14 nm within 5×5 μm^2 area. This work demonstrates the potential of TBCl in removing defects on GaN regrowth interfaces, laying a foundation for the development of advanced structure GaN electronic devices.

[1] Li, B *et al*., *ACS Applied Materials & Interfaces*, **13**, 53220-53226 (2021).

[2] Fu, H. *et al.*, *Materials Today*, 49, 296-323 (2021).

GR-Mon-B12 - Buffer-less growth of GaN on foreign substrates: Towards vertically-conducting heterostructures and heterojunction devices

1. Growth

Uiho Choi[1]
Zheng Hao[1], Ivan Kršić[1], Alessandro Floriduz[1], Francesco Marcantoni[1], Yuan Zong[1], Elison Matioli[1]
[1] Power and Wide-Band-Gap Electronics Research Laboratory (POWERlab), Institute of Electrical and Micro Engineering, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland

Abstract text: Vertical GaN devices are promising for high-power electronics due to the superior properties of GaN. Until recently, research has focused on growing high-quality GaN by heteroepitaxy due to the lack of homo-substrate. This typically requires buffers to mitigate large lattice and thermal mismatches and to address chemical property differences with the substrates (Fig. 1a, b). Despite advancements in growth technology, electrical devices based on heteroepitaxy GaN have mostly been limited to lateral or quasi-vertical types, rather than fully-vertical devices. This limitation arises because electrical conduction between GaN and the substrates is nearly impossible due to defective or highly-resistive buffers. As a result, the viable option for achieving a fully-vertical GaN-based device remains the use of GaN substrates or a substrate removal process.

Here, we present a novel method of growing GaN on $ScAlMgO_4$ (SAM), sapphire, and Si substrates without buffers, using only a trimethyl aluminum pre-flow treatment in metal-organic chemical vapor deposition (Fig.1c)[1-3]. Fig. 2-4 show that the buffer-less GaN on SAM, sapphire, and Si were successfully epitaxially grown without buffer, and confirm that the overall quality of buffer-less GaN is compliant and, to some extent, comparable to that of GaN with buffer.

Especially, it is worth noting that this buffer-less growth applies well to GaN growth on Si and holds significant promise for enabling electrical connection between them. This is very importantly for fully-vertical devices, in which the Si substrate can be a fully part of the device. We successfully grew thick GaN layers—up to 8 μm—without cracks using selective-area growth technique (Fig. 5) and demonstrated Schottky barrier diodes (SBDs) with conduction through the n-GaN/n^+Si heterostructure (Fig. 6a and b). We fabricated SBDs on such structure, by simply depositing the anode on the top GaN surface and the cathode on the bottom Si surface of the wafer, without any substrate removal or thinning process. The device exhibited a very low on-resistance (0.53 $m\Omega \cdot cm^2$), revealing the excellent conduction through the GaN/Si heterojunction.

We believe that these results open a pathway toward realizing high-performance heterojunction GaN-on-Si fully-vertical devices, and offer potential to be extended to other conductive wide-bandgap substrates.

GR-Mon-B13 - Bowing Engineering of AlGaN Drift Layers on GaN substrates for Vertical Power Devices

1. Growth

Byeongchan So[1]
Adamantia Logotheti[1], Jovana Malm[1], Dat Q. Tran[2], Minho Kim[2], Navya sri Garigapati[3], Plamen Paskov[2], Michal Bockowski[4], Erik Lind[3], Vanya Darakchieva[1]
[1] Center for III-Nitride Technology, C3NiT-Janzén, Solid State Physics and NanoLund, Lund University, Lund, Sweden
[2] Center for III-Nitride Technology, C3NiT-Janzén, Department of Physics, Chemistry and Biology (IFM), Linköping University, Linköping, Sweden
[3] Department of Electrical and Information Technology and NanoLund, Lund University, Lund, Sweden
[4] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, Warsaw, Poland

Abstract text: AlGaN offers exceptional properties such as a high critical electric field and superior Baliga's figure-of-merit, making it ideal for next-generation power devices. To fully leverage these advantages, a vertical device design using high-quality n-type GaN substrates is essential. However, a key challenge is "bowing," caused by the thermal expansion coefficient mismatch between the epi-layer and substrate, which can degrade device quality and yield. Even low Al composition in the AlGaN drift layer can induce significant curvature due to the thick layer. Therefore, optimizing crystal curvature is crucial for high-power vertical devices.

This work presents a bowing engineering approach for 5-µm-thick AlGaN drift layers (~Al 7%) grown on GaN substrates via MOCVD. Both HVPE and ammonothermal GaN substrates initially exhibited concave curvatures of approximately -0.1 m^{-1}, as measured by position-dependent X-ray measurement. After growing the AlGaN drift layer, curvatures increased to -0.27 m^{-1} (HVPE) and -0.5 m^{-1} (ammonothermal). To mitigate this, we deposited an AlGaN layer on the backside (N-polar face) of the GaN substrates, resulting in convex curvatures of 0.04 m^{-1} (HVPE) and 0.1 m^{-1} (ammonothermal). With this bowing engineering technique, we achieved a reduced curvature of -0.065 m^{-1} for the AlGaN drift layer on the Ga-polar side of the HVPE GaN substrate, comparable to or better than the substrate's curvature. We then fabricated Schottky Barrier Diodes (SBDs) to evaluate the effect of bowing engineering on device performance and yield. The extracted interfacial characteristics were state-of-the-art with an ideality factor $\eta = 1.04$, a barrier height $\varphi_b = 1$ eV, the turn-on voltage $V_{on} = 0.55$V, and a $R_{on} = 0.6$ mΩ cm^2. Furthermore, we observed a high current swing I_{ON}/I_{OFF} with I_{OFF} at -20V in the order of 10^{12}, demonstrating uniformity and low leakage in both forward and reverse bias conditions. The proposed bowing engineering approach also leads to improved yield as compared to conventional AlGaN drift layers.

GR-Mon-B14 - Fabrication of Cost-Effective GaN Templates with Low Density of Dislocations by Epitaxial Lateral Overgrowth

1. Growth

Irene Manglano Clavero[1]
Christoph Margenfeld[1], Jochen Bruckbauer[2], Paul R. Edwards[2], Jana Hartmann[1], Carol Trager-Cowan[2], Robert W. Martin[2], Andreas Waag[1]
[1] Nitride Technology Center, Institute of Semiconductor Technology, Technische Universität Braunschweig, Braunschweig, Germany
[2] Department of Physics, SUPA, University of Strathclyde, Glasgow, United Kingdom

Abstract text: GaN devices grown on sapphire substrates, such as LEDs, have been widely commercialized, as they can achieve high performance despite having a high density of dislocations. However, more demanding applications such as laser diodes and vertical transistors require a higher crystallographic quality for their reliable operation, which has so far necessitated growth on GaN bulk substrates. Their production cost is substantially higher and wafer sizes are still limited, which hinders the ubiquitous adaptation of this technology. Therefore, it is of great interest to develop large-area, inexpensive substrates.

Epitaxial lateral overgrowth (ELOG) is a method of producing high-quality, cost-effective templates. The initial appeal of this technique faded due to complications during growth and the challenge of scaling up structures. However, interest in this method has been reignited thanks to the work presented by Kyocera Corporation in 2023 [1]. Here, they proved that dislocation-free ELOG wings of more than 20 µm in width could be achieved, which is sufficient to accommodate whole optoelectronic devices such as microLEDs or laser diodes. While the device performance has been demonstrated, very little information on how to achieve these large ELOG wings in terms of the growth process was disclosed.

In this work, we will shed light onto this topic by demonstrating the growth of wide ELOG wings with widths exceeding 22 µm on GaN-on-sapphire templates, explaining the considerations needed to obtain such large ELOG structures [2]. Note that the challenge of growing these lies not only in achieving large dimensions, but also in avoiding the generation of new non-radiative defects that are associated with the crystallographic tilt of the wide ELOG wings. We show that this tilt can be significantly improved by changing growth conditions and that the formation of the aforementioned defects can be avoided. The tilt is characterized by X-ray diffraction, electron backscatter diffraction (EBSD) and cathodoluminescence (CL), with the complementary techniques allowing us to determine the real-space distribution of the wing tilt, and thus provide a better understanding of the growth process.

[1] Kamikawa, T., Cryst. Growth Des, 23, 7, 4855-4861 (2023)
[2] Manglano Clavero, I., Cryst. Growth Des, 24, 1, 279-292, (2024)

Band structure, phonons

2025-07-07
15:30 - 17:00
Band structure, phonons

PC-Mon-10* - Determination of the band splitting and hole effective mass of GaN from valence-band structure observed by angle-resolved photoemission spectroscopy

2. Physics and characterization

Akihira Munakata[1]
Seishu Arikawa[1], Yoshinori Nakagawa[2], Masaki Kobayashi[3]
[1] Department of Electrical Engineering and Information Systems, The University of Tokyo, Bunkyo-ku, Tokyo, 113-8656, Japan
[2] Nichia Corporation, 491 Oka, Kaminaka, Anan, Tokushima, 774-8601, Japan
[3] Department of Electrical Engineering and Information Systems, and Centre for Spintronics Research Network, The University of Tokyo, Bunkyo-ku, Tokyo, 113-8656, Japan

Abstract text: A wide gap semiconductor GaN is a promising material for power device application and has been intensively studied so far. The valence band (VB) of GaN consists of heavy-hole (HH), light-hole (LH), and crystal-filed splitting hole (CH) bands, and the parameters, that is, the band splitting Δ among these bands and the effective hole mass m^* of each band significantly affect the optical and electrical properties of GaN. Although theoretical and experimental studies have been performed to estimate Δ and m^*, the reported values have been inconsistent and still controversial [1-3]. In this study, we report the precise determination of the VB structure of GaN with high-resolution angle-resolved photoemission spectroscopy (ARPES) to elucidate Δ and m^* of each band experimentally.
Si-doped GaN single crystals were grown by the halide vapor phase epitaxy (HVPE) method. To obtain the clean surface, the samples were cleaved *in vacuo* at the *m*-surface plane. The ARPES measurements using synchrotron radiation were performed at BL-28 of the Photon Factory (PF), High Energy Accelerator Research Organization (KEK). The circular, linear-vertical, and linear-horizontal polarizations corresponding to *c*-, *s*-, and *p*-polarizations, respectively, were used for the measurements, which were performed at 30 K with the energy resolution of 21 meV.
In the ARPES spectra with *c*-polarization along the Γ-A direction of the GaN single crystal, HH, LH, and CH bands are observed. Since no surface state can be seen, the ARPES spectra mainly reflect the bulk electronic states. In contrast, only CH and HH (LH) are clearly visible with *s*- (*p*-) polarization. Then, the value of Δ between HH and LH bands is estimated from the energy difference of VBMs between the ARPES spectra taken with *s*- and *p*-polarizations. In addition, m^* of each band and Δ' between HH and CH bands can be estimated by fitting each band with a parabolic function. Based on the findings, we have succeeded in directly determining detailed band parameters with high resolution ARPES for the first time. The values of Δ and m^* obtained in this study likely explain the difficulty for the realization of the ohmic contact on p-type GaN and will be useful for device simulations.
[1] A. Punya *et al*., *Phys. Rev. B* **86**, 195147 (2012), [2] W. Shan *et al., Phys. Rev. B* **54**, 23 (1996), [3] M. Franz *et al., Phys. Rev. B* **99**, 195306 (2019).

PC-Mon-11 - Phonon structure in Nitride semiconductor

2. Physics and characterization
Tao Wang[1]
Hailing Jiang[2], Zhenyu Zhang[2], Ping Wang[2], Bo Shen[2], Xinqiang Wang[2]
[1] Electron Microscopy Laboratory, School of Physics, Peking University, Beijing 100871, China.
[2] State Key Laboratory for Mesoscopic Physics and Frontiers Science Center for Nano-optoelectronics, School of Physics, Peking University, Beijing 100871, China.

Abstract text: Phonons, the quantized vibrational modes of a crystal lattice, play a crucial role in determining the thermal properties of III-nitride semiconductors. By modifying the defect or crystal structure of the material, researchers can manipulate certain phonon modes and their dispersion.

In this study, we investigated phonon behaviors in 8-atom ring dislocation, prismatic stacking faults (PSF) of GaN and buckled 2D GaN using electron energy loss spectroscopy (EELS) supported by scanning transmission electron microscopy (STEM) at an atomic scale, combined with high spatial, energy, and momentum resolution.

We reveal vibrational modes localized on 8-atom ring GaN dislocation core atoms, corresponding to short-range interactions. Additionally, we observe phonon energy shifts driven by strain fields around the dislocation, representing long-range interactions. Ab initio calculations support these findings and draw out additional details. This work reveals how dislocations impose phonon scattering through atomic reconstruction and strain engineering[1].

PSF represents the most predominant grain boundaries in III-Nitrides. We identified localized atomic vibrational modes that result in defect phonon modes at 58-62 meV and 99-105 meV, which are absent in bulk GaN. Additionally, we directly observed the phonon dispersion of PSF and bulk GaN using the 4D-EELS technique. Our observations validate that PSF in GaN induces a smaller phonon energy gap compared to bulk GaN. This characteristic, along with the presence of defect modes, may intensify phonon scattering and lower thermal conductivity[2].

We extracted phonon signals from buckled 2D GaN and observed a significant blue shift in optical phonons. Furthermore, the phonon dispersion of bulk GaN and buckled 2D GaN along specific momentum paths was directly observed using the 4D-EELS technique. We found that buckled 2D GaN exhibits a larger gap between acoustic and optical phonons compared to bulk GaN[3].

Overall, phonon engineering in nitride semiconductors offers a powerful tool for tailoring material properties to meet the demands of various applications.

1、Jiang, Hailing; Wang, Tao; Wang, Xinqiang, https://doi.org/10.48550/arXiv.2409.10628

2、Zhang, Zhenyu; Wang, Tao; Wang, Xinqiang ;, Nature Communications, 2024, 15(1): 10436.

3、Jiang, Hailing; Wang, Tao; Wang, Xinqiang, Nature Communications, 2024, 15(1): 9052

PC-Mon-12 - Pump and probe Raman scattering analysis of phonon dynamics dominating carrier dynamics in III-nitride heterostructures including quantum wells

2. Physics and characterization

Yoshihiro Ishitani[1]
Yusuke Ishii[1], Yuki Watanabe[1], Thee Ei Khaing Shwe[1], Daisuke Iida[2], Motoaki Iwaya[3], Masatomo Sumiya[4], Bei Ma[1], Mohammed A. Najmi[2], Kazuhiro Ohkawa[2]
[1] Chiba University, Chiba, Japan
[2] King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
[3] Meijo University, Nagoya, Japan
[4] National Institute of Material Science, Tsukuba, Japan

Abstract text: Heat energy generation in semiconductor devices is a significant problem for improving device performance and energy consumption efficiency. Electron–longitudinal optical (LO) phonon interaction is the dominant origin of the degradation of device performance at room temperature or higher. In particular, this interaction in GaN and AlN is higher than that in GaAs by one order or more. Phonon exclusion outside of devices is a difficult task, but we have found some footholds. It is known that the LO phonons are decomposed to phonons of other optical modes and finally acoustic modes. The bottleneck of the spatial phonon transport is located at heterointerfaces. The amount of available information on this issue is quite limited while we are investigating methodologies to exclude phonon energy from the active region of devices and to investigate the phonon dynamics in semiconductors using pump-and-probe methods in Raman scattering spectroscopy, including time-resolved analysis. In this report, we show the results of transient Raman spectroscopy in sub-picosecond (ps) and sub-nanoseconds (ns) ranges. Samples are GaN films and $Ga_{1-x}In_xN$/GaN heterostructures, including quantum wells. The Raman scattering measurement systems have femtosecond (fs) pulse lasers with wavelengths of 785 nm and 262 nm and sub-nanosecond lasers of 532 nm and 266 nm. Stokes and anti-Stokes signals were analyzed. It was found that the anti-Stokes signal of the LO-phonon of GaN is yielded instantaneously after the irradiation of the 262 nm pulse, while the anti-Stokes signal of the E_2(high) mode takes its maximum at a few ps later. Considering the LO phonon lifetime of approximately 3 ps, the delay of the E_2(high) signal is attributed to its generation by the decomposition of the LO modes. The peak energy shift of the Stokes signal of the E_2(high) mode, indicating the temperature increase, shows the decay time of 20 – 30 ps, indicating the decay time to the acoustic or blind mode phonons dominating the anharmonic lattice oscillations. This information agrees with the imaging analysis of the phonon transport across the GaInN/GaN heterointerface, indicating the significance of the energy continuity of the E_2(high) mode at the heterointerface. Thus, the time-resolved Raman analysis in sub-ps to ns is a powerful measure for investigating the control lability of phonon decomposition processes.

PC-Mon-13* - Photonic Atom Probe analysis of AlGaN multilayer structures for UV lasers

2. Physics and characterization

Samba Ndiaye[1]
Ettore Coccato[2], Nissrine Alhelou[1], Subodh Kumar Gautam[1], Jesus Cañas[2], Névine Rochat[3], Adeline Grenier[3], Audrey Jannaud[3], Zineb Saghi[3], Jean-Luc Rouvière[4], Edith Bellet-Amalric[2], Eva Monroy[2], Lorenzo Rigutti[1]
[1] Groupe de Physique des Matériaux, CNRS, Université de Rouen Normandie, 76000 Rouen, France
[2] Univ. Grenoble-Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France
[3] Univ. Grenoble Alpes, CEA, LETI, 38000 Grenoble, France
[4] Univ. Grenoble Alpes, CEA, IRIG, MEM, 38000 Grenoble, France

Abstract text: Correlative microscopy, combining laser atom probe tomography (La-APT) and photoluminescence (PL), significantly advances the analysis of light-emitting materials such as semiconductors. The photonic atom probe (PAP) exploits the possibility of measuring PL from a specimen during its APT analysis [1], [2], providing a comprehensive understanding of semiconductor materials' characteristics and device performance. In this study, we analyzed a multilayer of AlGaN/AlN containing 10 quantum wells (QWs), grown by plasma-assisted molecular beam epitaxy, and emitting in the 190-300 nm spectral range [3]. Understanding the correlation between the microscopic characteristics of these heterostructures and their optical properties is crucial for optimizing these structures. The analyzed specimen exhibits spatial inhomogeneities and a significant dispersion of PL emission energy. We show how a correlative microscopy approach can explain different optical emission features of these structures, particularly the distinction between the optical signature of non-defective QWs and QWs lying within the defective regions of this superlattice. The results are interpreted though 6-band k.p calculations applied on 1D or 3D models issued from the APT composition maps. Furthermore, we identify the effect of a field-induced mechanical stress of around 2 GPa, manifesting as a spectral red shift of the PL lines during the PAP analysis.

PC-Mon-14 - Unveiling compliance effects of Al0.15Ga0.85N microdisks by X-ray diffraction

2. Physics and characterization

Maud Nemoz[1]
Lea Lacomblez[1], Sébastien Chenot[1], Blandine Alloing[1], Benjamin Damilano[1], Pierre-Marie Coulon[1]
[1] Université Côte d'Azur, CNRS, CRHEA, Valbonne, France

Abstract text: (Al,Ga)N's tunable bandgap (3.4–6.1 eV) makes it essential for deep UV LEDs used in disinfection, water purification, and sensing. However, heteroepitaxial growth of AlGaN on GaN induces tensile strain, leading to cracking beyond a critical thickness. While methods such as crack burial and porous layers help to mitigate strain, they are limited in Al composition range and may introduce defects.

In this work, we introduce and evaluate, using X-ray diffraction (XRD), the potential of a novel approach to manage the tensile strain in AlGaN grown on GaN by using compliant $Al_{0.15}Ga_{0.85}N$ microdisks. The fabrication of $Al_{0.15}Ga_{0.85}N$ microdisks consists first in depositing a thin layer (80 nm) of AlGaN with only 15% Al composition which remains completely strained on the GaN template. A first reactive plasma etching allows the formation of (GaN + $Al_{0.15}Ga_{0.85}N$) micropillars of 20 µm diameter, then the selective thermal etching of the GaN results in $Al_{0.15}Ga_{0.85}N$ microdisks on top of GaN nanopillars. The $Al_{0.15}Ga_{0.85}N$ microdisks thus formed exhibit a partial relaxation of their initial stress. A layer of 1 to 2 µm AlGaN of higher composition (20% to 75% in this study) is then deposited on the microdisks.

The AlGaN micropallets grown on the $Al_{0.15}Ga_{0.85}N$ microdisks does not exhibit the cracks typically found in AlGaN grown on GaN templates. The threading dislocation density, imposed by the initial GaN template, remains consistent throughout the nitride layers in the mid 10^8 cm^{-2}. Cathodoluminescence has been used to determine the optical quality, and the strain evolution of all the layers has been investigated by X-ray diffraction. The $Al_{0.15}Ga_{0.85}N$ microdisk shows a high compliance capacity: its elastic deformation goes from ε_a = + 0.4% before GaN under-etching to ε_a = -1.4% after an $Al_{0.8}Ga_{0.2}N$ regrowth. The XRD diagrams also made it possible to monitor the GaN strain evolution at each stage.

Obtaining AlGaN micropallets of high Al composition with a smooth surface, no cracks and no pits and low dislocation density allows the growth of high structural and optical quality multiple quantum wells. Thus, the management of the stress during the growth of AlGaN thanks to a compliant $Al_{0.15}Ga_{0.85}N$ layer provides a promising approach for the production of highly efficient UV microdevices.

Radio Frequency Devices 4 (Enhanced Performance)

2025-07-08
08:30 - 10:00
Radio Frequency Devices 4 (Enhanced Performance)

ED-Tue-1 - Heterogeneous Integrated Sub-THz Transceiver Front End

4. Electronic devices

James Hwang[1]
[1] Cornell University, Ithaca, NY 14853 USA

Abstract text: Heterogeneous integration of different kinds of chiplets on an interposer has been developed for digital and memory applications. Heterogenous integration for RF applications is just emerging. In this case, with only a few I/O channels, there is plenty of room in the bulk of the interposer for passives such as combiners, filters, duplexers, and antennas that are much more efficient than their thin-film counterparts. This makes it possible to have a complete RF front end on a chip (interposer). In particular, at sub-THz frequencies (100-300 GHz), substrate-integrated waveguides (SIWs) can have much lower loss than microstrip or coplanar transmission lines. With the signal fully enclosed in the SIW, transmit and receive channels can be placed next to each other without crosstalk. Thus, a linear phased array, with transceivers spaced within a half wavelength from each other, can be fabricated on the same interposer. In turn, the interposers can be stacked to form a 2D array. These approaches will be illustrated through the GaN-on-SiC technology. However, similar heterogeneous integration approaches are applicable to other device technologies and interposer materials.

ED-Tue-2 - Terahertz detector based on side-gate AlGaN/GaN HEMT for resonant and non-resonant detection

4. Electronic devices
Wei Yan[1]
Chenyang Jin[1], Yaru Kang[1], Yeran Li[1], Zhaofeng Li[1], Fuhua Yang[1], Xiaodong Wang[1]
[1] Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

Abstract text: Gallium Nitride-based High-Electron-Mobility Transistors (GaN HEMTs) exhibit significant potential in terahertz (THz) detection due to their high breakdown voltage, wide temperature compatibility, and excellent high-frequency characteristics. However, traditional HEMT THz detectors are constrained by oblique mode effects induced by an excessive gate width, leading to broadened resonant response peaks and reduced sensitivity. Consequently, distinct resonant responses were rarely observed in the experiments.

This study establishes a THz resonant detector based on a side-gate AlGaN/GaN HEMT (EdgeFET), in which the gate is deposited on both sides of the two-dimensional electron gas (2DEG) channel. This structure enabled the formation of a one-dimensional confined conductive channel in the lateral direction through electrical modulation, effectively suppressing oblique modes while maintaining the 2DEG concentration and mobility, thereby enhancing the resonant response.

To validate the design, EdgeFET detectors and traditional HEMT detectors were fabricated on commercial GaN wafers. A novel dry etching process with an Al_2O_3 mask and self-aligned process was employed to ensure steep mesa sidewalls and high-quality gate-channel interfaces. Experimental results demonstrated a maximum non-resonant responsivity (*Rv*) of 7.76 kV/W and a minimum noise-equivalent power (NEP) of 3.11 pW/Hz^0.5 at 300 K. At 77 K, the EdgeFET exhibited distinct resonant and nonresonant response peaks. The resonant peak center frequency shifted with the incident wave frequency, which is consistent with the model predictions. The *Rv* of the resonance at 259 GHz reached 3.5 times that of the maximum nonresonant frequency. Comparative experiments revealed that the EdgeFET achieved approximately twice the maximum resonant responsivity of traditional HEMTs, confirming the efficacy of oblique-mode suppression through electrical tuning.

Through theoretical modeling and experimental validation, this study elucidates the advantages of the side-gate AlGaN/GaN HEMT THz detectors. This study provides an innovative technological pathway for the development of high-sensitivity, low-noise, and compact THz detectors, offering significant implications for the commercialization of THz imaging and communication systems.

ED-Tue-3* - GaN-HEMTs for Low-Noise Applications at Cryogenic Temperatures: Effects of Gate Length Scaling

4. Electronic devices

Mohamed Aniss Mebarki[1]
Ragnar Ferrand-Drake Del Castillo[1], Denis Meledin[1], Erik Sundin[1], Mattias Thorsell[1], Niklas Rorsman[1], Victor Belitsky[1], Vincent Desmaris[1]
[1] Chalmers University of Technology

Abstract text: GaN HEMTs offer an attractive combination of high robustness and competitive low-noise performance for high-frequency applications, owing to their wide bandgap and excellent electron transport properties. Recently, GaN HEMTs have emerged as promising candidates for highly sensitive cryogenic applications, such as radio astronomy and quantum computing. Their cryogenic noise performance has been shown to be within a factor of 4–8 of state-ofthe-art technologies, suggesting further improvements through design and layout optimization [1–2].

Gate length (Lg) scaling enhances the cutoff frequency (ft) and reduce noise. However, beyond a certain threshold, further benefits from Lg reduction may be limited by short-channel effects (SCE). These effects can be mitigated through design trade-offs depending on epitaxial properties, device geometry, and operating conditions [3]. However, the cryogenic low-noise performance of GaN HEMTs has so far been studied only for 0.2-µm gate-length designs, highlighting the need to investigate the impact of Lg variation under cryogenic conditions.

In this study, GaN-HEMTs with Lg ranging from 0.15 to 0.5 µm were fabricated and characterized at room temperature (RT) and 4 K (CT). SCE are found to be more pronounced at CT, as manifested by increased threshold voltage shift at high VDS, calling for appropriate vertical scaling to mitigate performance degradation. Based on Sparameters and noise measurements, a small-signal and noise model was obtained, capturing a consistent gate-length dependence of the device's cryogenic behavior. The 0.15-µm design exhibited the best cryogenic noise performance of 6 K (0.09 dB) at 5 GHz.

Additionally, a delay time analysis was carried out to extract the contributions of the access regions, the region under the gate and the gate field-plates to the total transit delay. The results highlight two key conclusions. First, noise and ft improvements are attributed to enhanced electron velocity under the gate, peaking at ~1.2·107 cm/s at CT in the 0.15-µm design. Second, further noise reduction with decreasing Lg is limited by access resistances and field-plates parastic contributions to transit delay, by ~10% and 60 %, respectively. These findings provide design guidelines for optimizing the cryogenic low-noise performance of GaN HEMTs.

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ED-Tue-4* - NbN gated AlGaN/GaN Schottky Gate HEMT on (0001) 4H-SiC for high power applications: Improved DC Performance and Threshold Voltage Stability

4. Electronic devices

Umang Singh[1]
Ritam Sarkar[1], Soumyadip Chatterjee[1], Aakash Shandilya[1], Apurba Laha[1]
[1] IIT Bombay

Abstract text: ALGaN/GaN high electron mobility transistors (HEMT) are renowned for their outstanding performance in high power and high-frequency applications due to their high electron saturation velocity, high breakdown field and high thermal conductivity. The conventional method of controlling the operation of the 2DEG channel at AlGaN/GaN interface is achieved using a metal (e.g. Ni)-schottky gate leading to a metal-semiconductor HEMT (MSHEMT) type device. However, Ni, being a metal, cannot passivate surface states, leading to threshold voltage instability and current collapse. Use of gate dielectric such as Al2O3 or SiNx between metal and semiconductor to reduce gate leakage and surface passivation leads to issues such as threshold voltage stability, low gate capacitance leading to reduction of control that gate has over channel. Hence one of the desirable solutions would be to use a metallic material as gate that can also passivate the surface states on semiconductor surface.

NbN is a transition metal nitride that exhibits metallic behavior at room temperature and has been demonstrated to form a Schottky contact with GaN, with a work function ranging between 4.7 and 4.9 eV [1]. Therefore, if NbN is used as the gate contact material in an AlGaN/GaN HEMT, the resulting device will behave as an MSHEMT.

This work reports NbN as a schottky gate on AlGaN/GaN high electron mobility transistor (HEMT). We observed a reduction of gate leakage current and three order of magnitude improvement in ON/OFF ratio for NbN gated HEMT as compared to that of Ni/Au gated control HEMT sample. This reduction is attributed to passivation of semiconductor surface states by NbN leading to reduction in trap assisted tunneling. We measured an enhancement of transconductance (maximum) in case of NbN HEMT (85 mS/mm) as compared to control sample (78 mS/mm) which shows increase in gate control because of passivation of surface states by NbN. The subthreshold slope is also seen to decrease from 266 mV/decade for Ni/Au MSHEMT to 72 mV/decade for NbN MSHEMT. Lastly, our study confirms that the use of NbN as a gate could significantly improve the performance of all-nitride AlGaN/GaN HEMT with better threshold voltage stability and reduced hysteresis in transfer characteristics as compared to the conventional metal gated HEMT.

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ED-Tue-5* - GaN Varactor with linear C(V) realized through F plasma treatment

4. Electronic devices

Ragnar Ferrand -Drake Del Castillo[1]
Niklas Rorsman[1], Mattias Thorsell[2]
[1] Chalmers, Microwave Electronics Laboratory, 412 96, Gothenburg, Sweden
[2] SAAB AB, 412 89, Gothenburg, Sweden

Abstract text: An AlGaN/GaN varactor proof-of-concept is here demonstrated with a highly linear reverse bias Schottky gate C(V) characteristic. Linearity is essential for low-distortion RF applications [1], yet conventional GaN varactors often exhibit nonlinear tuning behavior. Given the widespread use of GaN MMICs in RADAR and 5G applications, integrating fully monolithic varactors represents a major step forward in RF performance, thus eliminating the need for discrete components [2]. Hence, parasitic inductive/capacitive effects can be curtailed and thermal management enhanced.

The tuning range and linearity of the C(V) profile (extracted from S-parameter measurements) is controlled via F plasma exposure and subsequent annealing prior to Schottky gate formation. The best results were attained using CF_4 plasma and 20 min 550 °C annealing, providing both an 80% larger tuning range C(-4 V)/C(-20 V) = 2.3, and more linear characteristics compared to reference device without F plasma treatment, with Q(-4 V,50 MHz) = 3.2×10^3).

All devices (except the reference) underwent 15 nm SiN_x passivation-first deposition, where the duration of the SiN_x gate opening was varied with different degrees of F plasma over-etching (100%, 125%, and 200%; denoted SHORT, MID, LONG) relative to the nominal thickness. F plasma exposure led to incorporation of charged states, F^- (acceptor state) and O^+ (donor state), impacting depletion region characteristics. Since both charged states are thermally instable within the annealing range utilized (550 °C to 800 °C) [3], [4], thermal treatment, (beyond promoting diffusion), plays a crucial role in charge state modulation.

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Defects and processing

2025-07-08
08:30 - 10:00
Defects and processing

PC-Tue-A1 - Annealing behaviors of vacancies and their impact on dopant activation in ion-implanted GaN studied by positron annihilation

2. Physics and characterization

Akira Uedono[1]
Kohei Shima[2], Shigefusa Chichibu[2], Shoji Ishibashi[3]
[1] Faculty of Pure and Applied Science, University of Tsukuba, Tsukuba, Ibaraki 305-8573, Japan
[2] Inst. Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai 980-8577, Japan
[3] Research Center for Computational Design of Advanced Functional Materials, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8568, Japan

Abstract text: The vertical GaN device architecture, compared to a lateral architecture, can offer advantages, such as a higher current density and breakdown voltage. Here, an optimization of the device processing is key for commercializing vertical devices. One of the critical building blocks is the selective area doping of impurities. The precise control of impurity concentrations and their profiles can be done using only ion implantation. The major drawback of ion implantation is the generation of high-concentration point defects due to atomic collisions. Such defects could relate to the degradation of electric properties and the reliability of devices. Thus, knowledge of annealing behaviors of point defects is essential. Positron annihilation spectroscopy is a useful technique for detecting vacancy-type defects in solids. This technique has been used to study process-induced defects in GaN [1–4]. In the present study, we used a monoenergetic positron beam to study the annealing behaviors of vacancy-type defects in ion-implanted GaN.

A process for activating Mg and its relationship with vacancy-type defects in Mg-implanted GaN were studied. Mg and N ions were implanted, and their concentrations in the subsurface region were on the order of 10^{19} cm^{-3}. The sequential implantation of N was found to enhance the activation of Mg. For N-implanted GaN before annealing, the major defect species were determined to Ga-vacancy related defects such as divacancy. After annealing after 1000°C, the clustering of vacancies was observed. Above 1200°C annealing, however, the size of the vacancies started to decrease, which was due to recombinations of vacancy clusters and excess N atoms in the damaged region, which was attributed to the origin of the enhancement of the Mg activation.

This work was supported in part by MEXT-Program of R&D of Next-Generation Semiconductor (JPJ005357), Creation of Innovative Core Technology for Power Electronics (JPJ009777), and JSPS KAKENHI (JP16H06427 and 21H01826).

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PC-Tue-A2 - Stable structures of (VGaVN)n defects in bulk GaN

2. Physics and characterization

Hiroyuki Ishihara[1]
Masato Oda[1], Tsuyoshi Miyazaki[2]
[1] Wakayama University, Japan
[2] National Institute for Materials Sciences, Japan

Abstract text: GaN is a promising material for power devices due to its wide bandgap, high breakdown voltage, and high electron saturation velocity. However, the lack of suitable substrates leads to a high defect density, which results in the degradation of device performance. For p-type GaN, it is reported that high Mg doping and annealing generate large-scale defects such as $(V_{Ga}V_N)_n$. While experimental studies observe these defects, their structural and electronic characteristics remain unclear. This study elucidates the atomic-scale stable structures and electronic states of $(V_{Ga}V_N)_n$ using large-scale first-principles calculations.

We employ the large-scale density functional theory (DFT) code "CONQUEST" with pseudo-atomic orbital basis sets and the multisite support function method to reduce computational cost. Various $(V_{Ga}V_N)_n$ configurations are examined with a supercell containing 1600 atoms, considering long-range structural effects and making interactions between vacancies in neighboring cells negligible. All atoms are fully relaxed until the Hellmann-Feynman forces are reduced below 0.0005 Hartree/Bohr. Defect formation energies and energy gains related to defect aggregation are systematically analyzed up to n = 6 to clarify the stability of various defect structures.

We reveal that the maximum energy gain for each n does not increase monotonically but peaks at n = 3, decreases at n = 4 and 5, and reaches another maximum at n = 6. This suggests that $V_{Ga}V_N$ defects tend to aggregate and grow, and the aggregated vacancy is stable especially at n = 3 and n =6. For models larger than n = 3, fewer dangling bonds contribute to their stability, and structures tend to form a void-like shape. Although the number of dangling bonds strongly influences the stability, there are also notable differences in the stability even among the various structures having the same number of dangling bonds. Note that, since the DOS differs for each n and structure, precise optical measurements may be able to identify the defect structures. The stability of large defects at n = 3 aligns with recent experimental observations, while no reports exist for n = 6 to our knowledge. This may be due to the lower stability of defects at n = 4 and 5.

PC-Tue-A3* - Electrically active defects in dilute AlxGa1-xN films

2. Physics and characterization

Piotr Kruszewski[1]
Vladimir Markevich[2], Lijie Sun[2], **Christopher Dawe**[2], Paweł Prystawko[1], Jerzy Plesiewicz[1], Matthew Halsall[2], Iain Crowe[2], David Binks[2], José Coutinho[3], Anthony Peaker[2]
[1] Polish Academy of Sciences, Institute of High Pressure Physics, Warsaw, Poland
[2] University of Manchester, Photon Science Institute, Manchester, United Kingdom
[3] University of Aveiro, i3N, Aveiro, Portugal

Abstract text: Deep-level defects can significantly influence the performance and reliability of (Al)GaN devices by acting as prominent recombination centers [1]. Despite their detrimental influence, the understanding of these deep-levels is limited, and the complexity increases further when alloying GaN with aluminium. Thus, understanding and identifying these deep-levels is critical in optimizing device control and achieving effective growth of dilute $Al_xGa_{1-x}N$ structures.

In this work, we have studied high-quality dilute $Al_xGa_{1-x}N$ ($x \leq 0.063$) samples grown by metal-organic vapor phase epitaxy (MOVPE) on highly conductive Ammono-GaN substrates [2]. This material has been characterized using conventional deep-level transient spectroscopy (DLTS) in conjunction with high-resolution Laplace-DLTS (L-DLTS) [3].

The DLTS spectra reveal an electron emission signal, commonly known as E3, which has been convincingly attributed to the Fe_{Ga} (0/-) level [4]. By utilizing L-DLTS, the broad E3 signal in $Al_xGa_{1-x}N$ can be resolved into discrete electron emission signatures caused by fluctuations in the number of Al atoms found in the second-nearest neighbour (2NN) shell, centred around the Fe_{Ga} impurity atoms. The theoretical probability of the Al concentration in the 2NN shell agrees with the experimental probabilities extracted from the L-DLTS peak intensities.

Moreover, this work demonstrates that the Fe_{Ga} (0/-) level in dilute $Al_xGa_{1-x}N$/GaN heterojunctions acts as a common reference level that is pinned to the vacuum level, as expected for energy transition levels of transition metals in isovalent compound semiconductors. This knowledge has been applied to determine the conduction (ΔE_c) and valence band offsets (ΔE_v) as a function of Al content, revealing band offsets that can be described by the relations, $\Delta E_c = 1.17x$ eV and $\Delta E_c = -0.95x$ eV, over the range of dilute $Al_xGa_{1-x}N$ material studied. These findings agree fairly well with the experimental results for actual $Al_xGa_{1-x}N$/GaN heterojunctions and theoretical predictions based on hybrid density functional theory [5].

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PC-Tue-A4* - Doping Characterization of Selectively Grown GaN PN Diodes: A Cathodoluminescence and Electrical Measurement Study

2. Physics and characterization

Zakariae M'QADDME[1]
Mohammed El Amrani[1], Névine Rochat[1], , Gwénolé Jacopin[2], Blend Mohamad[1], David Plaza Arguello[1], Thomas Kaltsounis[1], Matthew Charles[1], Julien Buckley[1], Łukasz Borowik[1]
[1] Univ. Grenoble Alpes, CEA-LETI, Grenoble 38000, France
[2] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France

Abstract text: Power electronic devices are fundamental in electrical energy conversion, with gallium nitride (GaN) emerging as a key material for next-generation power devices due to its high breakdown field and superior performance over silicon. However, challenges such as lattice mismatch, thermal expansion differences, and stress-induced cracking hinder efficient device fabrication. Selective Area Growth (SAG) has proven to be an effective method for mitigating these challenges, enabling the growth of thick GaN layers with reduced stress and defect density.

In this work, GaN-layers were grown on 200 mm Si(111) wafers using metal-organic vapor-phase epitaxy (MOVPE). The structure included AlN and AlGaN buffer layers, and Si-doped GaN layers to provide lateral conductivity between the anode and cathode in the pseudo-vertical diodes for the quasi vertical devices. An Al_2O_3 mask was deposited then patterned, before growing a 10 µm n-GaN drift layer and 600 nm pGaN layer by localized epitaxy forming mesas 100 µm in diameter. These structures were then processed into pseudo vertical p-n diodes. In forward bias, the diode exhibited an ideality factor of 2.5 and an on-resistance (Ron) of 12 $m\Omega \cdot cm^2$. Under reverse bias, the device demonstrated a high breakdown voltage (BV) of approximately 800 V. This BV demonstrates the device robustness despite a dislocation density of about 2.4×10^8 cm^{-2}, as determined by cathodoluminescence (CL) measurements.

To assess the doping distribution and uniformity in the layers, CL mapping was used as a high-resolution and non-destructive technique. By correlating near-band-edge (NBE) linewidth broadening with doping concentration, local carrier densities were mapped. The results showed a net doping concentration of $\sim 2 \times 10^{16}$ cm^{-3} in n-GaN layer and $\sim 1 \times 10^{17}$ cm^{-3} near the sidewalls. Mg doping uniformity was also examined, showing the presence of Mg in the top and on the sidewalls of the mesa. Scanning spreading resistance microscopy (SSRM) and scanning capacitance microscopy (SCM) were used to confirm the doping distribution. Additionally, capacitance-voltage (C-V) measurements corroborated the net doping concentration in the drift layer.

These findings emphasize the potential of SAG for advancing high-power GaN-based electronics by improving material quality and electrical performance.

PC-Tue-A5 - Defect characterization of monolithically stacked green/blue InGaN light-emitting diode structure using multiphoton-excitation photoluminescence

2. Physics and characterization

Tomoyuki Tanikawa[1]
Motoaki Iwaya[2], Masahiro Uemukai[1], Ryuji Katayama[1]
[1] Graduate School of Engineering, the University of Osaka, Suita, Osaka Japan
[2] Department of Materials Science and Engineering, Meijo University, Nagoya Japan

Abstract text: Monolithic integration of red/green/blue (RGB) InGaN-based light-emitting diodes (LEDs) has progressed for advanced micro-LED displays. One of the integration methods is epitaxial stacking of RGB InGaN LEDs via tunnel junctions. These devices often suffer from defect generation due to lattice mismatch of nitride semiconductor alloys. This study aims to investigate detailed defect characterization of monolithically integrated InGaN LEDs using multiphoton-excitation photoluminescence (MPPL), which allows nondestructive, three-dimensional defect imaging.

An InGaN blue/green tunnel junction LED structure was fabricated on a free-standing GaN substrate by metalorganic vapor phase epitaxy,[1] and characterized by MPPL.[2] First, the relationship between emission spectra and excitation wavelength was investigated to enhance the visibility of dislocations in the InGaN well layers. When the excitation wavelength was in the range of 740–840 nm, the MPPL emission from the InGaN well layers was enhanced compared to that from a GaN underlayer. This is because the carriers are excited by a two-photon absorption process in the InGaN layer, whereas they are excited by a three-photon absorption process in the GaN layer. After optimizing the excitation wavelength, deep luminescence from GaN was relatively suppressed, and MPPL images clearly showed defect distribution in the InGaN well layers. Next, MPPL imaging was performed using three photomultiplier tubes and several optical filters and the dark spot densities of the GaN substrate, blue InGaN well layer, and green InGaN well layer were compared. The detected wavelength ranges of MPPL emission were 382–388 nm, 419–465 nm and 512–608 nm. We observed the increase of the dark spot densities in the blue InGaN well layer ($\sim 10^5$ cm^{-2}) and the green InGaN well layer ($\sim 10^7$ cm^{-2}) while no dark spots were observed in the GaN substrate ($<10^5$ cm^{-2}), indicating the direct evidence for misfit strain relaxation by generating additional dislocations in both blue InGaN and green InGaN with respect to the underlayers. Further characterization results, including three-dimensional spectral analyses and local emission properties, will be presented.

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Nanowires

2025-07-08
08:30 - 10:00
Nanowires

PC-Tue-B1 - Ultraviolet Photodetection with GaN Nanowires: Advances in Fabrication, Architectures, and Performance

2. Physics and characterization

Elçin Akar[1]
Martien Ilse Den Hertog[2], **Eva Monroy**[1]
[1] Univ. Grenoble-Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France
[2] Univ. Grenoble-Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France

Abstract text: GaN-based nanowires have emerged as promising building blocks for next-generation optoelectronic devices, owing to their unique combination of wide bandgap, doping and heterostructuring capabilities, and excellent thermal and chemical stability. Their use as photodetectors is particularly promising, as their one-dimensional geometry enables a decoupling between the active area, responsible for optical absorption, and the electrical cross section, which governs the time response. The high surface-to-volume ratio enhances light-matter interaction but also makes these devices highly sensitive to surface states, which can hinder linearity and introduce persistent effects. These limitations can be mitigated by careful engineering of nanowire geometry, doping profiles, and heterostructure design.

This presentation reviews recent advances in GaN-based nanowire UV photodetectors, examining fabrication techniques, device architectures, and performance benchmarks. Developments in nanowire processing now enable a comparison between bottom-up and top-down approaches. Bottom-up growth allows for nearly defect-free heterostructures with flexible material combinations, whereas top-down fabrication, based on lithography and etching, provides precise and scalable control over nanowire dimensions and doping profiles, which are key parameters to ensure device uniformity and reproducibility.[1–3]

Most GaN nanowire photodetectors adopt a metal–semiconductor–metal configuration, which often exhibits sublinear photoresponse and response times in the millisecond range. Linearity can be restored in fully depleted nanowires,[4] or by engineering the axial internal electric fields. The latter can be implemented through insertion of heterostructures (polarization-induced field) or p–n or p–i–n junctions (built-in field).[1] For example, bottom-up nanowires with embedded GaN/AlN superlattices achieve bias-tunable spectral selectivity and responsivity enhancements up to two orders of magnitude. Under reverse-bias, surface-state effects are minimized, yielding a fast and linear photocurrent response, as demonstrated both in single-nanowire devices and in nanowire ensembles.[1,5]

In p–n or p–i–n devices, the photodetector performance is expected to improve due to the presence of the built-in field at the junction. Moreover, in such structures, integrating a p^+/n^+ tunnel junction enables the use of symmetric metal contacts. Such architectures exhibit diode-like I–V characteristics and improved linearity and speed under reverse bias, both in the case of bottom-up and top-down fabricated nanowires.[3,6]

Finally, planarized nanowire ensembles encapsulated in hydrogen silsesquioxane (HSQ) maintain the advantages of nanowire geometry, including linearity, spectral selectivity and fast switching, demonstrating their viability for large-area photodetection solutions.

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PC-Tue-B2 - Deep UV-C down to 225 nm from core-shell AlN pillar arrays

2. Physics and characterization

Lucie Valéra[1]
Lucas Jaloustre[2], Saron Sales de Mello[2], Sebastien Labau[2], Camille Petit-Etienne[2], Erwine Pargon[2], Gwénolé Jacopin[3], **Christophe Durand**[1]
[1] Univ. Grenoble Alpes, CEA, PHELIQS, Grenoble, France
[2] Univ. Grenoble Alpes, CNRS, CEA/LETI-Minatec, Grenoble INP, Institute of Engineering and Management University Grenoble Alpes, LTM, Grenoble, France
[3] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France

Abstract text: UV-C LEDs represent an alternative to toxic mercury lamps, however their efficiency remains critically low. Wire-based UV-LEDs offer a compelling solution to traditional planar structures, benefiting from enhanced light extraction, non-polar oriented sidewalls and reduction of extended defects. While our recent studies have demonstrated the feasibility of GaN wire-based UV-LEDs,[1,2] this approach is unsuitable for UV-C due to strain issue.[3] As a result, AlN microwires emerge as an ideal template for future non-polar deep UV-C emitters.

In this work, we demonstrate non-polar GaN/AlN deep UV-C emitters grown on the sidewalls of AlN pillar arrays using metal-organic vapor phase epitaxy. The process involves three steps. First, organized AlN pillars with m- and a-oriented hexagonal shapes and varying spacings are fabricated via top-down etching from AlN templates.[4] Second, an AlN overgrowth is carried out at high V/III ratio (27000) to achieve smooth sidewalls.[5] Third, ultrathin GaN/AlN quantum wells (QWs) are grown in a core-shell geometry. Transmission electron microscopy images reveal a QW thickness of approximately 0.8 nm with the presence of Al-content. Cathodoluminescence (CL) analysis reveals that the a-plane sidewalls of AlN pillars exhibit strong deep UV-C emission. By decreasing the pillar spacing from 15 to 2 μm, the emission wavelength shifts from 240 to 225 nm. This tuning could be either attributed to a lower lateral growth rate or an enhanced Al incorporation into the wells in dense arrays, enabling spectral engineering. Temperature-dependent and time-resolved CL revealed unique carrier recombination dynamics within the (Al)GaN/AlN QWs attributed to the presence of trapping levels. Using an integrating sphere, the external quantum efficiency (EQE) of core-shell AlN emitters is estimated to be 0.2 % at 230 nm under CL excitation. This work provides a new CL method for EQE measurements to develop high-efficiency UV-C emitters and paves the way for next-generation deep UV-C devices.

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PC-Tue-B3 - Investigation of InGaN buffer layer inclusion in InGaN/GaN Nanowire Superlattice: A way towards high efficiency red light emission

2. Physics and characterization

Krishnendu Sarkar[1]
Stefano Pirotta[1], Nidel Tchoulayeu[1], Quang-Chieu Bui[1], Laurent Travers[1], Martina Morassi[1], Stephane Collin[1], François H. Julien[1], Jean-Christophe Harmand[1], Noëlle Gogneau[1], Maria Tchernycheva[1]
[1] Centre de Nanosciences et Nanotechnologies, University Paris-Saclay, CNRS, UMR9001, 10 Boulevard Thomas Gobert, 91120, Palaiseau, France

Abstract text: Nanowire (NW) axial InGaN/GaN heterostructures are building blocks for light emitting diodes (LEDs). NWs are free from dislocations due to lateral stress relaxation through NW sidewalls and therefore, are effective pseudo-substrates for epitaxially growing InGaN axial nanostructures [1]. InGaN/GaN NW heterostructure based blue/green LEDs have been developed by many groups. Extending the spectral emission towards red while maintaining high efficiency requires the growth of high In-content InGaN which is troublesome due to its large lattice mismatch with GaN producing large internal strain and alloy demixing. This strain makes difficult the incorporation of high concentration of In atoms in the InGaN lattice and is the controlling force for the compositional pulling effect in InGaN [2]. Moreover, crystallographic point defects detrimental for the LED efficiency are prone to appear in InGaN.

In the present contribution, our endeavor is to find an epitaxial strategy to both counterbalance the compositional pulling effect for achieving In-rich InGaN insertions while at the same time to reduce the point defects in the InGaN/GaN superlattice grown by PAMBE. For this, an InGaN buffer with low In content is inserted between the GaN NW base and the InGaN/GaN NW superlattice, this buffer being separated from the superlattice with a very thin GaN barrier. The influence of the InGaN buffer growth conditions on trapping the defects from InGaN/GaN superlattice has been investigated with high resolution cathodoluminescence spectroscopy at room temperature and at 10 K. The optical properties and spatially mapping of the heterostructure along the NW axis are also investigated. Statistical study of the luminescence spectra recorded for InGaN/GaN NW superlattices demonstrates a considerable reduction in the point defects spectral signatures at both RT and 10 K with InGaN buffer. We also show red-emission from the superlattice. The InGaN buffer then functions as a strain counterbalancing and defect trapping layer to simultaneously compensate the pulling effect and to reduce the defects in red-emitting InGaN insertions.

References:

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[2] S. Pereira et al., Phys. Rev. B, 64, 205311 (2001)

PC-Tue-B4* - The origin of multiple maxima of efficiency in InGaN-GaN nanowires single quantum well light-emitting-diodes

2. Physics and characterization

Amadéo Vibert[1]
Mehdi Daanoune[1], Quentin Rafhay[2], Jean-Yves Duboz[3]
[1] Aledia, 38130 Echirolles, France
[2] Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, Grenoble INP, CROMA, 38000 Grenoble, France
[3] Université Côte d'Azur, CNRS, CRHEA, 06560 Valbonne, France

Abstract text: Micro Light-Emitting-Diodes (MicroLEDs) are expected to penetrate the display market and allow the development of improved augmented reality or virtual reality products. InGaN/GaN nanowires are very promising for these applications, thanks to their high luminescence and directivity. However, there is still room for significant improvement in the efficiency of these 3D nanostructures. The shape of the efficiency curve of MicroLEDs is often described as a bell-shape with a single maximum of performance, which can be displaced to higher or lower current density, depending on the technical applications. However, recent measurements on test samples showed a double maximum of efficiency which could not be explained with basic models. This study presents experimental results along with numerical simulation of a single quantum wells (SQW) nanowire Light-Emitting-Diodes. Using a Poisson-drift-diffusion solver, the origin of the double maximum of efficiency will be presented and compared to experimental results. It is found that the double maximum of efficiency originates from the emission of two different planes of growth at two different wavelengths. The first maximum of efficiency comes from the emission from the C plane QW and the second maximum from the semi-polar plane. Based on these results, possible geometrical modifications are presented in order to optimize the development of nanowires MicroLEDs.

PC-Tue-B5 - Multimodal Micro-Laue XEOL Analysis of Light-Emitting Core-Shell Nitride Micro-Wires

2. Physics and characterization

Beatriz De Goes Foschiani[1]
Jean-Sebastien Micha[2], Samuel Tardif[1], Olivier Ulrich[1], **Joel Eymery**[1]
[1] University Grenoble Alpes, CEA, IRIG MEM NRX, F-38000 Grenoble, France
[2] University Grenoble Alpes, CEA, IRIG SYMMES STEP, F-38000 Grenoble, France

Abstract text: The development of advanced functionalities in nitride materials relies on precise growth control, process optimization, and high-resolution characterization techniques. Focused X-ray beams provide innovative solutions for correlatively analyzing strain and light emission by combining micro-Laue diffraction and X-ray excited optical luminescence (XEOL). Additionally, qualitative x-ray fluorescence mapping giving composition estimation complements strain and emission analysis.

This work presents recent experimental and analytical advancements at the BM32 beamline of the European Synchrotron Radiation Facility, focusing on GaN micro-wires with InGaN/GaN multiple quantum wells (MQWs). By correlating structural characterization—epitaxial relationships, strain, and orientation—with light emission, we establish comparisons with techniques such as TEM, EBSD, cathodoluminescence, and photoluminescence. Notably, micro-Laue diffraction enables high-resolution deviatoric strain tensor measurements down to 10^{-4}, surpassing EBSD in strain quantification.

GaN micro-wire emission is studied using XEOL hyperspectral analysis, while local strain variations and lattice rotations are extracted via micro-Laue diffraction. The technique benefits from a small beam size (~300 nm), short acquisition time (~1 s), and polychromatic Laue diffraction, allowing multiple Bragg reflections to be recorded without sample rocking, enabling rapid, high-resolution strain mapping.

XEOL analysis reveals distinct emission features from the wires, including contributions from MQWs, near-band-edge peaks, and defect-related bands. Micro-Laue analysis is demonstrated using diffraction pattern indexing and refinement with the LaueTools software.

By combining these methods, we correlate visible emission with crystalline structure and clarify growth-induced effects such as shell-induced strain and emission gradients (11.3 meV/µm) and Indium concentration between ~7.8% to ~10.2%. Fast scanning techniques enable statistical sample characterization, paving the way for production monitoring and systematic screening of optoelectronic materials and microstructures. Potential applications to various MOVPE-grown materials will be discussed.

UV LEDs

2025-07-08
08:30 - 10:00
UV LEDs

OD-Tue-1 - Interband AlGaN Tunnel Junctions for Ultraviolet Light Emitting Diodes and Lasers

3. Optical devices

Siddharth Rajan[1]
[1] The Ohio State University, Columbus, OH 43210, USA

Abstract text: This presentation will outline recent advances in the development of high Al-content interband tunnel junction ultraviolet emitters. The high ionization of acceptors, poor hole transport properties, and the high p-contact resistance to AlGaN make it very challenging to realize high-performance emitters, especially in the UV emission wavelength range. Interband tunnel junctions provide an promising approach to overcome these fundamental challenges by enabling non-equilibrium injection of carriers in p-type AlGaN layers. This presentation we will discuss recent advances in realizing highly efficient tunneling injection and their integration into UV LEDs.

We will first discuss the use of heterostructure and polarization engineering to realize transparent AlGaN tunnel junctions for UVB and UVA emission, tunnel junctions to realize multi-active region LEDs at these wavelengths, and edge-emitting lasers emitting in the UVA wavelength range. We will then discuss the design metal-semiconductor tunnel junctions, where we use Al-based contacts to make contact to p-AlGaN through a thin heterostructure. Finally, we will discuss out work on realizing tunnel junctions targeting far-UV emission LEDs (< 250 nm), with efficient tunneling in AlGaN with Al-content > 80%.

OD-Tue-2 - UVA to far UVC AlGaN quantum well growth on AlGaN micropallets for ultraviolet microdevices applications

3. Optical devices

Léa Lacomblez[1]
Maud Nemoz[1], Philippe Vennéguès[1], Ileana Florea[1], Maksym Gromovyi[1], Blandine Alloing[1], Benjamin Damilano[1], **Pierre-Marie Coulon**[1]
[1] Université Côte d'Azur, CNRS, CRHEA, Valbonne, France

Abstract text: Size reduction of LEDs toward µLEDs has been a hot topic in the visible range mainly driven by Virtual Reality and Augmented Reality applications. The UV community is slowly exploring different methods for the fabrication of UV µLEDs, in order to increase the light extraction, one of the key drawbacks of AlGaN based UV devices. Of course, application is also driving the fabrication of UV µLEDs, notably for non-line of sight UV communication. So far, reports focus on top-down plasma etching approach which is known to generate surface damages and nonradiative recombination centers at the sidewall surface that limit the overall efficiency of µLEDs.

In this work, we present a novel top-down/bottom-up approach to fabricate AlGaN micropallets on which AlGaN multiple quantum wells (MQWs) emitting from the UVA to the far UVC wavelength range have been grown. First, we describe the overall fabrication process of the micropallets which combines top-down etching, selective thermal etching and bottom-up regrowth. Overall, scanning electron microscopy and atomic force microscopy (AFM) highlight a *c*-plane surface without cracks and pits and with reasonable surface roughness. A dislocation density in the mid 10^8 cm^{-2} can be estimated from AFM scans, transmission electron microscopy (TEM) and panchromatic cathodoluminescence (CL) imaging. Room temperature CL measurements demonstrate that the *c*-plane MQWs emission can be tuned from 330 to 230 nm depending on the Al composition and QW thickness which has been measured by TEM. Hyperspectral CL maps reveal non-uniformities of the MQWs emission characteristics across the *c*-plane surface (intensity, linewidth and peak wavelength) which arise from and preferential island step flow growth. The quality of MQWs is assessed by measuring the ratio of photoluminescence intensities at room and low temperatures. Finally, we grow a UVB LED structure and demonstrate the feasibility of transferring a micropallet array onto a Si substrate for device processing.

In conclusion, the combination of high structural and optical quality, along with the ability to transfer the micropallet onto a host substrate, holds promise for enhancing efficiency of UV devices (e.g. IQE, LEE and hence EQE) across the entire UV wavelength range.

OD-Tue-3* - A Comprehensive Study on Optical Polarization, Stress Relaxation, and Failure Mechanisms in AlGaN-Based UVC LEDs

3. Optical devices

Honglin Gong[1]
Renlong Yang[1], Renzhu Zhang[1], Weijie Guo[1], Huanting Chen[2], Lihong Zhu[1], Yijun Lu[1], Zhong Chen[1]
[1] Xiamen University
[2] Minnan Normal University

Abstract text: This study explores the complex degradation behaviors of AlGaN-based UV-C light-emitting diodes (LEDs) under constant current stress and a stable heat sink temperature over a 500-hour period. Using 2D cathodoluminescence (CL) at each degradation stage, we analyze emissions from the multiple quantum wells (MQW) layer and the N-AlGaN layer in detail. Peak wavelength mapping and intensity distribution pseudo-color images enhance our understanding of defect generation and intensity decline across various layers during degradation. To complement this analysis, we employ focused ion beam and scanning electron microscopy (FIB/SEM) to visually inspect defects and observe the deterioration of the P-metal's Cr/Al layer after 48 hours of degradation. The CL emission results align closely with the SEM images, offering a comprehensive visual method to pinpoint defect locations and examine the failure mechanisms of UV-C LEDs. Additionally, Raman spectroscopy reveals strain relaxation at different stages of degradation, exemplified by the blue shift of the E_2^H phonon peak from the P-GaN layer of AlGaN-based LEDs, measured from various orientations: back, front, and side views. This technique allows us to thoroughly examine stress relaxation beneath the P-metal while the N-metal remains unchanged. This comprehensive investigation provides critical insights into the intricate degradation mechanisms of UV-C LEDs, shedding light on their performance under extended stress conditions. Furthermore, the spatial distribution of transverse magnetic (TM) and transverse electric (TE) polarized photons contributing to the luminescence of the MQW structure has been effectively distinguished using angle-resolved cathodoluminescence (ARCL). The complementary contributions of TM and TE photons at specific angles are identified through ARCL and validated by finite-difference time-domain (FDTD) simulations. This distinction offers flexibility in selecting different emission modes based on application requirements. The presented approach not only opens up new opportunities for enhanced UV-C light extraction but also provides valuable insights for future advancements in device fabrication and epitaxial film growth.

OD-Tue-4 - Experimental and Theoretical Insights into the Relaxed or Strained 230 nm far-UVC LEDs as a Function of Quantum-Well Numbers

3. Optical devices

M. Nawaz Sharif[l]
Hiromitsu Sakai[2], Kohei Fujimoto[3], Yuya Nagata[3], Hiroyuki Yaguchi[3], Muhammad Ajmal Khan[1], Hideki Hirayama[1]
[1] RIKEN Cluster for Pioneering Research (CPR), 2-1 Hirosawa, Wako, Saitama, 351-0198 Japan
[2] Shin-Etsu Chemical, Japan
[3] Saitama University, Saitama 338-8570, Japan

Abstract text: In this study, we investigated the influence of the number of multi-quantum wells (MQWs) on the performance of either relaxed or strained AlGaN-based 230 nm-band far-ultraviolet-C (far-UVC) light-emitting diode (LED) using experimental and theoretical studies. The relaxed far-UVC LEDs were grown by MOCVD on a 4 μm thick AlN template on c-plane sapphire. Subsequently, the heteroepitaxy of undoped $Al_{0.86}Ga_{0.14}N$ buffer (500 nm thick), and a 1.7 μm thick Si-doped n-$Al_{0.86}Ga_{0.14}N$ buffer layer were grown. The multi-quantum wells (MQWs) consist of a n-fold (n: 2, 4, 8, 12, and 22) with QW and barrier (1 nm $Al_{0.94}Ga_{0.06}N$ barrier with 3.5 nm $Al_{0.86}Ga_{0.14}N$ well), a 6 nm ud-$Al_{0.94\rightarrow0.86}Ga_{0.06\rightarrow0.14}N$ final barrier and a 9 nm thick p-AlN electron blocking layer. The LED is completed by a 75 nm Mg-doped p-$Al_{0.9}Ga_{0.1}N$ layer and finally a p-GaN layer (75 nm thick) on top.

The threading dislocations (TDs) of AlN are approximately 1×10^9 cm^{-2}. The relaxation ratio (R-ratio) of the 1.7 μm-thick AlGaN (Al=86%) buffer layer grown on ud-AlGaN was 35%. As a result, the maximum EQE of 0.35 % in 232 nm LED was obtained using 4-fold MQWs. As the number of QWs increases, there is a distinct decline in the EQE, resulting from reduced internal quantum efficiency (IQE), even though the carrier injection efficiency (CIE) is increasing. This is attributed to the relaxed MQWs underneath the n-AlGaN layer affecting the Piezo-electric field in the QW. In contrast, using a coherent structure (low R-ratio: 0%), resulting in high IQE and CIE simultaneously, which is attributed to the compressed strain of the n-AlGaN layer mitigating the Piezo-electric field in the QW and p-side layers including the electron blocking layer (EBL). The low R-ratio underneath the MQWs is also critical for promoting the transverse electric (TE)-mode emission (for high light extraction efficiency (LEE)).

We investigated theoretically the influence of QW numbers on 230 nm far-UVC LED while considering a high R-ratio of 35% and TDs (1×10^9 cm^{-2}) in n-AlGaN using SiLENSe. The CIE increases and IQE decreases as the number of QWs increases. Overall, the product of CIE and IQE is higher with a lower number of 8-fold QWs. On the other hand, for a R-ratio of 0 % referred to as pseudomorphic growth of far-UVC LED with TDs of 1×10^4 cm^{-2}, both CIE and IQE increase as the number of QWs increases.

OD-Tue-5 - Layer transferred UV emitting hBN/AlGaN heterostructures

3. Optical devices

André Perepeliuc[1]
Ali Kassem[1], Rajat Gujrati[1], Phuong Vuong[1], Vishnu Ottapilakkal[1], May Tran[1], Ashutosh Srivastava[1], Tarik Moudakir[2], Paul Voss[1], Suresh Sundaram[1], **Jean Paul Salvestrini**[1], Abdallah Ougazzaden[1]
[1] GT-CNRS IRL
[2] Institut Lafayette

Abstract text: Hexagonal boron nitride (hBN) is an ultra-wide bandgap 2D semiconductor possessing a significant potential for DUV applications as a possible alternative to Al-rich aluminum gallium nitride (AlGaN)-based structures which faces several limitations (high activation energy of magnesium dopants in the p-doped region, need of an electron blocking layer). So the engineering of p-doped regions is a major issue for the realization of efficient DUV LEDs. This can be potentially alleviated by use of p-doped hBN. Indeed, hBN can be p-doped using Mg [1] and it is transparent in the UV permitting photons to be extracted. Moreover, a favorable band alignment permitting hole transport from hBN to Al(Ga)N allows h-BN to act as an EBL [2], removing the need for an additional resistive layer. Consequently, Mg-doped hBN has potential for realization of efficient pn junctions with n-AlGaN, which will serve as the foundation for integration of DUV MQWs. p-hBN/n-AlGaN heterojunctions were fabricated using a dry-selective lift-off transfer of Mg-doped hBN layer on top of n-AlGaN. Electrical contacts were used as mechanical stressors to provide structural rigidity to hBN layers as well as enabling selective lift-off. These junctions exhibit a rectifying behavior with a rectification ratio of approximately 3e5 at 3V. When junctions were forward biased, UV emission around 262 nm was measured. This emission corresponds to recombinations in the n-AlGaN layer, demonstrating good hole injection in the structure. Full LED structures were then fabricated by integrating UV MQWs into these junctions. Fabricated UV LEDs successfully emit around 290 nm serving as a proof of concept for future layer transferred p-hBN/MQWs/n-AlGaN structures in which the Al-content is increased to go toward DUV emission. The selective pick and place process used to build these LEDs has multiple advantages. First, it allows independent optimization of the p-side as well as of the n-side which includes the quantum wells. Secondly, UV MQWs are protected from the high temperatures needed for high hBN material quality growth and thus their thermal stability is not affected.

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Epitaxy for devices

2025-07-08
08:30 - 10:00
Epitaxy for devices

GR-Tue-1 - Low-cost Epitaxial Growth and Device Processing Technologies for Early Social Implementations of GaN-based Devices

1. Growth

Hiroshi Amano[1]
[1] Nagoya University

Abstract text: During this decade, many Si-based power devices will be replaced with high-efficiency and lightweight GaN-based power devices. Increasing information traffic will heighten the need for high-power, high-frequency devices for ultra-broadband wireless communications. GaN-based high-frequency devices will be the most promising candidates that meet the demands of the future data-driven society.

One of the most serious problems hindering the social implementation of GaN-based devices is the high manufacturing cost. MOVPE is commonly used for the mass production of GaN-based device structures, but the high cost of raw materials and carbon contamination from the raw materials are its problems. Our group is attempting to establish an HVPE technique for device fabrication.

For the early commercialization of GaN-based devices, it is necessary to establish a device fabrication process that is compatible with the Si-device fabrication process. In-plane junctions are commonly used in Si devices because they can be achieved by ion implantation and damage caused by ion implantation can be repaired by annealing. For GaN, many types of damage exist, including anion and cation vacancies and interstitial atoms and their complexes. Therefore, it is difficult to repair damaged GaN devices by simple annealing techniques. We have attempted to establish an annealing technique to repair ion-implanted damage under atmospheric pressure and realized p—n junction diodes that exhibit high reverse voltage and low resistance under forward bias.

The formation of low-resistance ohmic contacts, especially p-layers, is one of the key issues in the stable operation of high-power devices. We are attempting to achieve a low-resistance ohmic contact to the p-GaN layer even with a low doping concentration of $10^{17}cm^{-3}$ by annealing metallic Mg on the p-type GaN surface.

In this presentation, I would like to discuss low-cost epitaxial growth and device process.

Acknowledgements: This work was partly supported by JST as part of ASPIRE, grant number JPMJAP2311, MEXT-program for creation of innovative core technology for power electronics, grant number JPJ009777, and JSPS KAKENHI grant number JP22H00213. The author thanks all the members of Amano—Honda Laboratory in CIRFE, Nagoya University for fruitful discussions.

GR-Tue-2* - Epitaxy of > 7 µm thick GaN drift layers on Si (111) for fully vertical power devices

1. Growth

Sondre Michler[1]
Youssef Hamdaoui[2], Sarad Thapa[1], Sven Besendörfer[3], Farid Medjdoub[2], Elke Meissner[3]
[1] Siltronic AG, München, Germany
[2] CNRS IEMN, Villeneuve-d'Ascq, France
[3] Fraunhofer Institute for Integrated Systems and Device Technology IISB, Erlangen, Germany

Abstract text: Vertical GaN-on-Si(111) power devices potentially offer significant advantages over their lateral counterpart, including higher threshold voltage, increased current density, and higher breakdown voltage without compromising the device size [1]. Using silicon as a substrate is cost-effective due to its large diameter and low cost, making it appealing for industrial use. Moreover, the Si substrate can be locally removed under the active area of the device to realize a fully vertical current flow [1]. However, challenges remain in the epitaxy of sufficiently thick GaN drift layers on Si to facilitate high breakdown voltages due to the significant thermal and lattice mismatch inherent in the heteroepitaxial system.

In this work, GaN-based PN structures with drift layers thicker than 7 µm, capable of achieving 1200 V breakdown voltages, are grown on 6" Si(111) substrates using an industrial metal-organic chemical vapor deposition reactor. Utilizing a novel buffer based on an AlN/AlGaN superlattice that incorporates islands with optimized geometry, the threading dislocation density is drastically reduced. This, in turn, allows sufficiently compressive stress to be maintained in the subsequent active GaN layers during growth, compensating for the thermal mismatch with the substrate [2]. It was found that the geometry of the islands, which form on V-pits present in the AlN nucleation layer, can be effectively controlled by adjusting the growth temperature. Leveraging this buffer concept, crack-free GaN-based PN structures with a drift layer thickness of 7.4 µm (10 µm total thickness) on 6" Si(111) substrates were achieved, with an absolute wafer bow < 50 µm and a low threading dislocation density of 3.6×10^8 cm^{-2} [3]. Electrical characterization of fully vertical PN diodes on this wafer revealed a 1220 V non-destructive breakdown with avalanche capability, accompanied by a low $R_{on,sp} \sim 0.5$ $m\Omega cm^2$ [4]. These results pave the way for high-performance GaN-on-Si vertical power devices operating in the kilovolt range.

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[2] S. Michler, et al., Physica Status Solidi (b), 2400019 (2024).
[3] S. Michler, et al., Physica Status Solidi (a), 2400544 (2024).
[4] Y. Hamdaoui, et al., IEEE Transactions on Electron Devices, 10758680 (2024).

GR-Tue-3 - Growth of low carbon GaN:Si

1. Growth

Seiji Mita[1]
Shashwat Rathkanthiwar[2], Pegah Bagheri[2], Pramod Reddy[1], Dolar Khachariya[1], Ronny Kirste[1], Ramón Collazo[2], Zlatko Sitar[3]
[1] Adroit Materials
[2] North Carolina State Univeristy
[3] North Carolina State University

Abstract text: The demand for next-generation kV-class power electronics is rapidly increasing for applications in electric motor drives, energy storage, power conversion, and energy transportation. GaN-based vertical diodes and switches, enabled by highly conductive single-crystal GaN substrates, offer significantly improved efficiency, with Baliga's figure of merit outperforming conventional Si-based devices by several orders of magnitude.

A critical requirement for these high-voltage power devices is the development of thick, n-GaN drift layers with uncompensated doping in the low-10^{15} cm^{-3} range. Achieving this requires precise control over the metal-organic chemical vapor deposition (MOCVD) growth process, as unintentional carbon (CN_NN) incorporation poses a significant challenge to maintaining reliable doping at such low concentrations.

In this study, it is shown that by tailoring MOCVD growth conditions, carbon incorporation can be minimized, enabling the controlled formation of low-carbon GaN:Si layers essential for the realization of high-performance kV-class power devices. Specifically, we demonstrate controlled Si doping in the 10^{15} cm^{-3} range with room temperature mobility exceeding 1000 cm^2/Vs and carrier concentrations similar to Si doping levels. This was achieved by managing point defects through chemical potential control (CPC) and defect quasi-Fermi level (dQFL) control to minimize carbon-related compensation and mobility collapse.

Finally, GaN grown on semi-insulating substrates using both CPC and dQFL control exhibited stable and controllable doping (5×10^{15} to 2×10^{16} cm^{-3}) with high mobility (>1000 cm^2/Vs at RT) due to C_N concentrations below 10^{15} cm^{-3}. Finally, temperature-dependent Hall-effect analysis confirmed a maximum mobility of 4000 cm^2/Vs at 120 K. In combination, these results will enable a new generation of power diodes.

GR-Tue-4 - Controlling Mg doping profile in vertical GaN p–n junction diode grown by halide vapor phase epitaxy with n/p-separated nozzles

1. Growth

Chihiro Nishiwaki[1]
Naoki Fujimoto[2], Shugo Nitta[3], Takashi Murayama[1], Hirotaka Watanabe[2], Atsushi Tanaka[2], Yoshio Honda[2], Hiroshi Amano[2]
[1] School of Engineering, Nagoya University, Nagoya, Japan
[2] Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan
[3] Innovation Center for Semiconductor and Digital Future, Mie University, Tsu, Japan

Abstract text: Halide vapor phase epitaxy (HVPE) has gained attention for its use of carbon-free sources and high growth rate, which enables the growth of thick drift layers in a short time with low impurity concentrations [1]. Our group has reported the vertical GaN p–n junction diode (PND) grown by HVPE [2]. However, because of the adsorption of Mg source molecules to the reactor wall, unintentional Mg doping and a slow increase in Mg concentration ([Mg]) occur. In addition, the Fe concentration ([Fe]) increases rapidly at the p–n interface, which could cause reverse leakage current. To improve these impurity profiles, we have introduced a new HVPE reactor with an n-type GaN growth nozzle and a p-type GaN growth nozzle. The n-type and p-type GaN are grown separately as the wafer holder moves between these nozzles. It enables the supply of the Mg source to the p-type GaN growth nozzle during n-type GaN growth, which may steepen the [Mg] profile and prevent the increase in [Fe] at the p–n interface. Hereafter, this reactor is referred to as the "separated nozzle HVPE" system.

The vertical GaN PND structures were grown using the separated nozzle HVPE system on free-standing n^+-GaN (0001) substrates grown by HVPE. An 8.8-μm-thick n-GaN drift layer with a Si concentration ([Si]) of 5.2×10^{16} cm^{-3} was grown at the n-type GaN growth nozzle. Following the drift layer, a 0.7-μm-thick p-GaN layer with a [Mg] of 1.7×10^{19} cm^{-3} was grown at the p-type GaN growth nozzle. For the growth of the p-GaN layer, MgO was used as a Mg source. The depth profile of the [Mg] of the PND structure was characterized by secondary ion mass spectrometry (SIMS). In addition, vertical PNDs were fabricated to measure the electrical properties of devices.

According to the SIMS results, the [Mg] in the n-type GaN drift layer was 6×10^{14} cm^{-3} and increased steeply to 1.1×10^{19} cm^{-3} at the p–n interface within 87 nm without sharp increase in [Fe], which clearly shows the advantage of using the separated nozzle HVPE reactor. Additionally, the vertical GaN PNDs with low leakage current were fabricated. The results were comparable to those grown by MOVPE.

This work was supported by MEXT-Program for Creation of Innovative Core Technology for Power Electronics Grant Number JPJ009777.

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[2] K. Ohnishi *et al*., Appl. Phys. Lett. **119**, 152102 (2021).

GR-Tue-5 - 1200 V lateral GaN MOS-High Electron Mobility Transistors on 200 mm silicon wafers

1. Growth

Simona Torrengo[1]
Cédric Masante[1], Stéphane Becu[1], Aurélien Olivier[1], Matthieu Lafossas[1], Florent Gréco[1], Rémi Riat[1], Etienne Nowak[1], Matthew Charles[1]
[1] Univ. Grenoble Alpes, CEA, LETI, 38000 Grenoble, France

Abstract text: Gallium Nitride (GaN) conducts electrons more efficiently and withstand higher electric fields than Silicon (Si). It exceeds the performances of Si in terms of speed, temperature, and power handling and it is replacing Si-based devices in several radio frequency and power conversion applications. For the latter, GaN devices offer higher power efficiency, lower switching losses, and increased power density than Si-based ones, making them ideal for applications like power supplies, inverters, electric vehicle charging systems, and data centers.

To meet the requirements of innovative industrial and automotive applications, we developed a GaN lateral high electron mobility transistor (HEMT) on Si substrates for a new range of 1200 V applications. GaN epitaxy on silicon (GaN-on-Si) presents numerous challenges linked to lattice and thermal expansion coefficient mismatch between Si and GaN. Growing thick GaN layers of sufficient quality for the operation of a transistor required extensive optimization of the growth parameters. In particular, buffer thickness, the super-lattice (SL) thickness, surface condition, wafer curvature, had to be simultaneously well controlled. There is little information about this kind of processing, since GaN-on-Si technology is mostly used for applications up to 650 V, while 1200 V GaN-on-Si devices are still under research due to the challenging thick epitaxy required.

The growth development was carried out at CEA-LETI on a 200 mm AIXTRON close-coupled showerhead (CCS) metal organic vapor phase epitaxy (MOVPE) tool, using an AlN/AlGaN SL up to 6 µm in thickness while maintaining the bow of 200 mm wafers in an acceptable range. At the same time, improvement of the surface morphology was achieved. These wafers were initially characterized by vertical IV measurements showing breakdown voltage > 1550 V, as well as physical characterizations to evaluate crystallographic properties, surface morphology properties and surface defects.

The wafers were then processed into MOS-HEMT transistors with leakage current through the substrate <100 nA/mm (25 °C) and <10 µA/mm (150 °C) at 1200 V on MOS-HEMT. A variety of power and test transistors were analyzed, showing excellent BV vs specific R_{on} trade off, comparable with or better than state of the art HEMTs on silicon, SiC and sapphire substrates.

Radio Frequency Devices 5 (Enhanced Performance)

2025-07-08
10:30 - 12:00
Radio Frequency Devices 5 (Enhanced Performance)

ED-Tue-6 - Device scaling and reliability of RF GaN HEMTs

4. Electronic devices

Enrico Zanoni[1]
Francesco De Pieri[1], Andrea Carlotto[1], Manuel Fregolent[1], Alberto Cavaliere[1], Marco Saro[1], Carlo De Santi[1], Fabiana Rampazzo[1], Isabella Rossetto[1], Gaudenzio Meneghesso[1], Matteo Meneghini[1]
[1] Department of Information Engineering, University of Padova, Padua, Italy

Abstract text: Scaling of GaN HEMTs for application to millimeter-wave power amplifiers requires to re-design device epitaxial layers in order to reduce short-channel effects, at the same time controlling frequency dispersion due to deep levels and guaranteeing linearity. Currently, electron confinement and control of substrate current is achieved thanks to a Fe-doped or C-doped GaN buffer layer below the undoped GaN channel. Unfortunately, both impurities introduce defects in GaN: Fe enhances the density of a level at approximately 0.56 eV from conduction band, resulting in significant current collapse due to a dynamic positive threshold voltage shift. C atoms at nitrogen vacancies (C_N) introduce an acceptor level at 0.8 eV – 0.9 eV from the valence band, responsible for dynamic on-resistance effects, slow charge redistribution, memory effects and hot-electron degradation. These parasitic effects become critical for scaled (L_g £0.15 mm) devices, as in general a trade-off is established between control of short-channel effects and reduction of trap-induced dispersion phenomena. For these reasons, alternative designs of epitaxisl layers are being investigated; one option consists in separating the C-doped layer from the channel electrons by means of an AlGaN barrier, which prevents the interaction of channel electrons with C_N traps; more radically, in “bufferless” structures a thin undoped GaN channel is grown directly on top of the AlN nucleation layer, by adopting growth conditions which minimize defectivity.

While deep level effects related with Fe and C compensation have been extensively studied, characterization of dispersion in devices adopting wide bandgap backbarriers is still limited. Main results obtained up to now can be summarized as follows: (1) increasing the thickness of the undoped GaN channel reduces dispersion and current collapse, but short-channel effects are worsened, thus suggesting that trapping occurs at the channel/backbarrier interface; (2) good control of dispersion and short-channel effects can be achieved by optimizing the Al content in the backbarrier; (3) after a reverse-bias stress test, devices which adopt a backbarrier show a transconductance “overshoot” which is due to electroluminescence emission and consequent trap photoionization, resulting in a dynamic negative threshold voltage shift which occurs during g_m measurements; (4) finally, dispersion effects due to backgating can occur in bufferless devices even without implying the presence of deep levels, due to charge redistribution (Maxwell-Wagner effect).

ED-Tue-7 - Impact of Buffer Removal on Current Collapse and Performance of Scaled RF GaN HEMTs

4. Electronic devices
Deniz Erus[1]
John Niroula[1], Pradyot Yadav[1], **Tomás Palacios**[1]
[1] Massachusetts Institute of Technology, Cambridge, USA

Abstract text: Gallium nitride (GaN) high electron mobility transistors (HEMTs) are essential for next-generation high-power and high-frequency electronics due to their high breakdown voltage, electron density, and mobility. However, conventional GaN HEMTs suffer from defects in the buffer region, which lead to current collapse, threshold voltage drift, and lower current levels.

We investigate the effects of buffer removal on device performance using electrothermal TCAD simulations in Silvaco Victory. These simulations are calibrated with experimental data from temperature-dependent TLM and Hall measurements, and verified with I-V measurements on fabricated GaN-on-Si HEMTs.

Our work uses a lateral AlGaN/GaN HEMT structure with an 18-nm AlGaN barrier, 150-nm GaN channel, 1.59-µm GaN buffer, and 100-µm Si substrate, with L_g=100 nm, L_{gs}=100 nm, and L_{gd}=800 nm. Traps are introduced in both the AlGaN barrier (E_{TA}=0.6 eV, E_{TD}=0.3 eV, N_T=1×10^{16} cm^{-3}) and the GaN buffer (E_{TA}=0.4 eV, N_T=5×10^{16} cm^{-3}) [1]. We compare three device variants: a conventional HEMT, a buffer-free HEMT, and a buffer-free HEMT with a 250-nm AlGaN back-barrier added beneath the channel.

Buffer removal leads to a significant DC performance improvement, a 20% increase in peak drain current from 1.2 A/mm to 1.5 A/mm at V_{DS} = 10V and V_{GS} = 2V, by eliminating deep acceptor traps that deplete the 2DEG [2]. Adding a back-barrier further enhances the current by 6% (to 1.6 A/mm) and improves short-channel behavior through better 2DEG confinement.

Overall, our results indicate that removing the buffer and incorporating a back-barrier can significantly enhance GaN HEMT performance by increasing current density and improving thermal properties. This approach is promising for more efficient and reliable high-power and high-frequency applications.

Acknowledgements

This work was supported in part by Center 7 SUPREME, an Semiconductor Research Corporation (SRC) program sponsored by DARPA, award #145105-21913; and by SOITEC, award #034982-00001.

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ED-Tue-8 - Electro-thermal Co-design of GaN-on-GaN HEMTs Achieved by Stepped-Carbon Doped Buffer for RF Applications

4. Electronic devices

Mei Wu[1]
[1] xidian university

Abstract text: GaN high-electron-mobility transistors (HEMTs) are promising for microwave applications due to their high saturation velocity, dense 2DEG density and high critical electric field. Compared with the heteroepitaxial GaN structures, GaN-based devices on the lattice-matched GaN substrates with low dislocation density can effectively suppress the current collapse, improve the reliability, and enhance the RF power performances. The high output power requirement of the application makes the high operating voltage of the device necessary, which relies on the doping design of the buffer layer. However, the introduction of impurities can affect phonon-impurities scattering and thus the thermal conductivity of GaN epilayer. This problem is more significant for devices on GaN substrates with low thermal conductivity compared to those on SiC substrates. Therefore, the electro-thermal co-design of the GaN epilayer becomes essential for GaN-on-GaN HEMTs. How to optimize the electrical and thermal properties simultaneously for GaN-on-GaN structures is crucial and remains under explored. In this work, we present, for the first time, an electro-thermal co-design for GaN-on-GaN HEMTs, including (i) the influence mechanism of impurities on heat transfer, (ii) the modulation of doping on electric field and carrier transportation, (iii) the precise characterization of the thermal properties for each GaN layer. A stepped-Carbon doped buffer was proposed to realize the synergistic modulation of the electro-thermal performances. Record output power density (Pout) of 15.1 W/mm, 14.8 W/mm with peak power added efficiency (PAE) of 57.2% and 48.2% were achieved at 2 GHz and 3.6 GHz, respectively. The comprehensive analysis of the epilayer doping design and the outstanding RF power performance achieved through the C doped buffer are of great significance for advancing the RF application of GaN-on-GaN devices in the future.

ED-Tue-9 - Impact of carrier density and mobility interplay on the intrinsic performance of Al-rich (Al,Ga)N-channel high-electron-mobility transistors

4. Electronic devices

Badal Mondal[1]
Pietro Pampili[1], Jayjit Mukherjee[2], David Moran[2], Peter J. Parbrook[1], Stefan Schulz[1]
[1] Tyndall National Institute, University College Cork, Cork, Ireland
[2] James Watt School of Engineering, University of Glasgow, Glasgow, UK

Abstract text: High-electron-mobility transistors (HEMTs) based on ultra-wide bandgap Al-rich aluminum gallium nitride, (Al,Ga)N, alloys hold great potential for high-temperature, high-frequency, and high-power applications, including jet engine, 6G communication, and electric cars.[1] Central to the operation of (Al,Ga)N-based HEMT devices is the density and mobility of the two-dimensional electron gas (2DEG) formed at the channel-barrier interface. In general, these 2DEG characteristics depend on alloy composition and individual layer thicknesses of the HEMT heterostructures. However, previous theoretical studies often simplified these dependencies by assuming a constant 2DEG density over the entire parameter space, neglecting the impacts of experimental constraints in real devices.[2]

In this work,[3] using self-consistent Schrödinger-Poisson simulations that explicitly incorporate layer thickness, alloy composition, and strain fields while accounting for experimental constraints, we reveal strong dependencies of 2DEG characteristics on these device parameters. We demonstrate that the common assumption of a constant 2DEG density leads to experimentally challenging design constraints and often misjudges the intrinsic device performance. We reveal a critical trade-off between 2DEG density and mobility: while a higher Al composition contrast between the channel and barrier enhances the 2DEG density, it also increases alloy disorder scattering, thereby reducing mobility. We show that this interplay between 2DEG density and mobility can result in a higher intrinsic device performance and thereby greater application potential for (Al,Ga)N-based HEMTs than previously predicted. Specifically, our simulations show that Al-rich (x=0.5–1.0) $Al_xGa_{1-x}N$-channel HEMTs outperform conventional GaN-channel HEMTs at and above room temperature for experimentally feasible structures.

This work thus highlights the importance of detailed device simulations to fully exploit the application potential of (Al,Ga)N-based HEMTs. By elucidating the trade-offs between 2DEG properties and device parameters with realistic modeling, this study provides important guidance for designing next-generation high-performance Al-rich (Al,Ga)N-channel HEMTs.

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ED-Tue-10 - Experimental Demonstration of Avalanche operation in lateral normally-off 100 V GaN HEMTs

4. Electronic devices

Riccardo Fraccaroli[1]
Matteo Dell'Andrea[1], Manuel Fregolent[1], Mirco Boito[1], Isabella Rossetto[1], Carlo De Santi[1], Gaudenzio Meneghesso[1], Enrico Zanoni[1], Eleonora Canato[2], Alessio Pirani[3], Giansalvo Pizzo[3], Cristina Miccoli[4], Alfio Russo[4], Maria Eloisa Castagna[4], Ferdinando Iucolano[4], Matteo Meneghini[5]
[1] Department of Information Engineering, University of Padova, Padova (PD), Italy
[2] STMicroelectronics, via C. Olivetti 2, 20864 Agrate Brianza (MB)
[3] STMicroelectronics, via Tolomeo 1, 20007 Cornaredo (MI)
[4] STMicroelectronics, Str. Primosole 50, 95121, Catania (CT)
[5] Department of Information Engineering, University of Padova, Padova (PD), Italy; Department of Physics and Astronomy, University of Padova, Padova (PD), Italy

Abstract text: Over the last decade, normally-off power GaN high electron mobility transistors (GaN HEMT) found application in many power conversion systems. So far, it has been considered that GaN lateral transistors do not show avalanche capability, contrary to Si and SiC devices [1], and this may represent an issue in terms of device reliability.

This paper demonstrates that avalanche operation is indeed possible on 100V E-mode GaN HEMTs with sub-micrometer gate length, in presence of a weak sub-threshold leakage current. The dependence of the avalanche voltage on a) gate voltage and b) device geometry is analyzed; also, c) the positive temperature coefficient of the avalanche voltage is demonstrated.

In "**strong" pinch-off** (V_{GS}=-7 V) the devices reach breakdown (BD) at V_{DS}=223 V (V_{DIEL}) with steep current (I_{DS}) increase and consequent **catastrophic failure**. This failure is ascribed to the breakdown of the dielectric between gate and drain.

In "**reference" pinch-off** (V_{GS}=0 V), devices reached BD at V_{DS}=160 V (V_{AVAL}), with **no catastrophic failure**. In this conditions, a higher drain-source conduction current is present (I_{DS}<1nA at 100V), compared to V_{GS}= -7 V (I_{DS}<10pA at 100V). This subthreshold leakage initiates impact ionization (i.i.), with consequent avalanche process when V_{DS} increases, resulting in a sustainable increase in I_{DS}. This process "clamps" V_{DS} to V_{AVAL}, protecting the device from dielectric failure.

Measurements as a function of device geometry show that an increase in L_G results in a suppression of short-channel effects, with consequent decrease in drain-source leakage and increase in V_{AVAL}.

We found **confirmation of avalanche hypothesis by spectrally resolved electroluminescence** (EL) measurement on devices during off state (V_{GS}=0 V) constant current stress: Bremsstrahlung radiation due to hot electron (<2.5 eV) together with 3.4 eV band-to-band emission were observed on the device. This latter EL component demonstrates the generation of holes due to i.i. events [2].

Finally, we demonstrated that V_{AVAL} has a **positive temperature coefficient**. $I_{DS}V_{DS}$ performed at different temperatures on the same device, by adjusting gate voltage to obtain the same subthreshold

leakage at all temperatures, show an increase in V_{AVAL} with temperature, according to avalanche theory [3].

[1] 10.1109/APEC.2017.7931015

[2] 10.1109/JEDS.2024.3454334

[3] 10.1063/1.1754731

Acceptors in nitrides

2025-07-08
10:30 - 12:00
Acceptors in nitrides

PC-Tue-A6 - Study of Beryllium Acceptor States in Aluminum Nitride via Cathodoluminescence Analysis

2. Physics and characterization

Yingying Lin[1]
Jia Wang[2], Wentao Cai[3], Haitao Wang[3], Maki Kushimoto[4], Yoshio Honda[3], Hiroshi Amano[3]
[1] Deep Tech Serial Innovation Center, Nagoya University, Nagoya, Japan
[2] Institute for Advanced Research, Nagoya University, Nagoya, Japan
[3] Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan
[4] Department of Electronics, Nagoya University, Nagoya, Japan

Abstract text: Acceptor states in AlN have attracted significant interest due to their critical role in the modulation of p-type conductivity. Recently, Ishii et al. reexamined the Mg acceptor binding energy in AlN using photoluminescence (PL) measurements, revealing a significant shallower energy than previously theorized. Be, another potential acceptor when substituting Al sites, has received limited attention, with few experimental data available on its acceptor binding energy in AlN.

In this study, Be-doped AlN was prepared by implanting Be ions into unintentionally doped AlN epitaxial layers via metalorganic vapor phase epitaxy (MOVPE) on sapphire substrates, followed by rapid thermal annealing at 1300 ^{o}C for 20 minutes. Secondary ion mass spectrometry (SIMS) analysis confirmed a bulk Be concentration of ~10^{19} cm^{-3}.

Temperature-dependent cathodoluminescence (CL) spectroscopy was primarily employed to probe the optical properties of the doped material. High-resolution near-band-edge CL spectra acquired at 10 K revealed distinct features in Be-doped and undoped AlN. For undoped AlN, spectral peaks exhibited a ~20 meV blue-shift relative to literature values, attributed to biaxial strain (~–0.2%) arising from thermal expansion mismatch mismatch between AlN and sapphire. Using elastic constants and deformation potentials, the total strain-induced bandgap blue-shift was estimated as ~30 meV for fully strained AlN, consistent with our observations.

In Be-doped AlN, two additional peaks emerged at 6.08 eV and 5.96 eV. The 6.08 eV feature is assigned to the neutral Be acceptor bound exciton ($Be^{0}X$), with a binding energy of 44.1 meV. Thermal quenching of the $Be^{o}X$, luminescence was observed above 60 K and vanished near 100 K. Arrhenius analysis of the $Be^{o}X$ intensity temperature dependence indicated a two-step activation mechanism. The activation energy was determined to be 66.4 ± 3.3 meV in the high temperature range (70-100 K) and 7.3 ± 1.1 meV at lower temperatures (20-60 K). This behavior suggests an initial exciton delocalization below 60 K, followed by ionization of the bound exciton at elevated temperatures. To our knowledge, this is the first comprehensive CL-based determination of the Be acceptor binding energy in AlN.

PC-Tue-A7 - The BeGa-ON-BeGa complex as the shallowest acceptor in GaN

2. Physics and characterization

Michael Reshchikov[1]
Denis Demchenko[1], Benjamin McEwen[2], Shadi Shahedipour-Sandvik[2]
[1] Department of Physics, Virginia Commonwealth University, Richmond, VA 23220, USA
[2] College of Nanoscale Science and Engineering, SUNY-Albany, Albany, NY 12203, USA

Abstract text: Wide-bandgap semiconductors, such as GaN, AlN, and AlGaN, attract significant attention due to their numerous applications in optical and high-power devices. However, despite the successful development of GaN-based technology, efficient *p*-type doping remains difficult because Mg, the only currently viable acceptor in these semiconductors, is still somewhat deep in GaN (the acceptor level is E_A = 0.22 eV). It becomes too deep for *p*-type doping in AlGaN with increasing Al content (E_A = 0.5-0.6 eV in AlN). The Be_{Ga} acceptor was suggested as an alternative *p*-type dopant. There are several reports on conductive *p*-type GaN:Be, and even *p*-type AlN:Be, yet these materials are more often semi-insulating. A shallow acceptor level at E_A = 0.113 eV above the valence band was experimentally found in GaN and initially mistakenly attributed to the isolated Be_{Ga} acceptor. This level is responsible for the photoluminescence (PL) band (called the UVL_{Be}) with the zero-phonon line (ZPL) at about 3.38 eV.

Here, we present the results of a combined theory/experiment study of the UVL_{Be} band [1], which was detected in about fifty Be-doped GaN samples grown by metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) under various conditions. Our first-principles calculations, using HSE functional tuned to fulfill the generalized Koopmans' condition, attributed this PL band to the $Be_{Ga}O_NBe_{Ga}$ complex [1], which could be the shallowest acceptor in GaN with E_A = 0.113 eV. However, these calculations also predict a dual nature of this acceptor, i.e., a coexisting deep level of this defect at 0.34 eV above the valence band. The dual nature of the $Be_{Ga}O_NBe_{Ga}$ acceptor is predicted theoretically, but no confirmation of it has been currently found in the experimental data.

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PC-Tue-A8 - Passivation of Be and C acceptors in GaN by hydrogen

2. Physics and characterization

Michael Reshchikov[1]
Oleksandr Andrieiev[1], Dexian Ye[1], Denis Demchenko[1], Benjamin McEwen[2], Shadi Shahedipour-Sandvik[2]
[1] Department of Physics, Virginia Commonwealth University, Richmond, VA 23220, USA
[2] College of Nanoscale Science and Engineering, SUNY-Albany, Albany, NY 12203, USA

Abstract text: Hydrogen plays a crucial role in GaN growth and processing. It can form electrically neutral complexes with acceptors during growth, which significantly increases acceptor incorporation. For example, post-growth annealing is necessary for the dissociation of $Mg_{Ga}H$ complexes to activate Mg acceptors and achieve conductive *p*-type GaN. In this work, we demonstrate that other acceptors, such as C and Be, also form complexes with hydrogen similar to Mg. The effect of thermal annealing of GaN on photoluminescence (PL) was investigated. In samples moderately doped with Be, the Be_{Ga}-related yellow luminescence (YL_{Be}) band intensity decreased by up to an order of magnitude after annealing in N_2 ambient at temperatures T_{ann} = 400-900 °C. We explained this by the release of hydrogen from unknown traps and the passivation of the Be_{Ga} acceptors. A similar drop of PL intensity at T_{ann} = 350-900 °C was observed for the C_N-related YL1 band in unintentionally C-doped GaN. It was attributed to the passivation of the C_N acceptors by hydrogen released from unknown defects. In this case, the formation of the C_NH_i complexes was confirmed by the observation of the rising BL2 band associated with these complexes. At T_{ann} > 900 °C, both the YL_{Be} and YL1 intensities in GaN:Be and GaN:C were restored, which was explained by the removal of hydrogen from the samples. Experimental results were compared to the first principles calculations of complex dissociation and hydrogen diffusion paths in GaN.

PC-Tue-A9* - Exploring Diffusion for Selective-Area Current Blocking Layers in Gallium Nitride Using Magnesium-Doped Spin on Glass-Based Technique

2. Physics and characterization

Nishita Sinha[1]
Zhengliang Bian[1], Jennifer Toy[1], Alberto Marcuzzi[2], Gaudenzio Meneghesso[2], Matteo Meneghini[3], Ke Zeng[4], Srabanti Chowdhury[1]
[1] Department of Electrical Engineering, Stanford University, Stanford, CA, USA
[2] Department of Information Engineering, University of Padova, Via Gradenigo, 6/b - 35131 Padova, Italy
[3] Department of Information Engineering, University of Padova, Via Gradenigo, 6/b - 35131 Padova, Italy; Department of Physics and Astronomy, University of Padova, Via F. Marzolo, 8 - 35131 Padova, Ital
[4] Department of Electrical Engineering, Stanford University, Stanford, CA, USA; Department of Electrical Engineering, University of North Carolina, Charlotte, NC, USA

Abstract text: P-doping and its activation is a well-known hurdle in GaN that has primarily been overcome by introducing magnesium (Mg) during epitaxial growth (MOCVD or MBE), followed by an annealing to diffuse out hydrogen particularly for MOCVD processes [1]. This problem is especially acute in buried selective-area p-type structures required for vertical GaN devices such as current aperture vertical electron transistors (CAVET) and MOSFETs [2,3]. Prior work has implemented buried p-layers or current blocking layers via implantation or regrowth [4]. These are both complex processes that may create defects, necessitating a careful look into more gentle processes. Diffusion is one such process that has recently been explored as a potential method of achieving p-type doping in GaN [5,6].

Our previous work has demonstrated that annealing a Mg-doped spin-on-glass (SOG) source can effectively diffuse Mg into gallium oxide and lead to up to 1 kV current blocking capability [7]. In this work, we investigated the viability of SOG-based diffusion as a cost-effective method to achieve selective-area p-doping in GaN.

Performing this diffusion process at 1000 ºC resulted in a Mg concentration >1e18 cm^{-3} up to 0.7 μm into GaN substrates. The electrical properties of the diodes fabricated using this diffusion process were measured and compared to reference Schottky barrier diodes without Mg diffusion. Under forward bias, Mg-diffused devices exhibited a turn-on voltage of 4 V whereas reference SBD exhibited a turn-on voltage of 0.7 V, indicating creation of a built-in potential by the Mg diffused layer. Under reverse bias, reference SBDs exhibited breakdown voltages of ~50 V. Mg diffused diodes demonstrated higher breakdown voltages, with repeatable values of ~170 V for samples diffused at 1050 ºC and ~400 V for samples diffused at 1000 ºC.

Mg-diffused diodes also exhibited 430 nm electroluminescence, an emittance that has been seen in GaN pn junctions due to the presence of an Mg-acceptor level.

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PC-Tue-A10* - New insights into Mn3+ in GaN from high-frequency/high-field EPR

2. Physics and characterization

Viktor Rindert[1]
Mathias Schubert[2], Michał Boćkowski[3], Vanya Darakchieva[1]
[1] Solid State Physics, Lund University, Sweden
[2] Department of Electrical and Computer Engineering, University of Nebraska-Lincoln, USA
[3] Institute of High-Pressure Physics of the Polish Academy of Sciences, Warsaw, Poland

Abstract text: Magnetic semiconductors based on III-V compounds, particularly GaN and AlN doped with transition metal ions, have garnered significant attention for their potential in spintronic and quantum applications. These materials enable the manipulation of electron spin in devices such as spin-valve transistors, field-effect transistors, and light-emitting diodes. One of the major challenges in spintronics is achieving room-temperature ferromagnetism, and GaMnN has emerged as a promising candidate due to its high-temperature ferromagnetic response. Understanding the behavior of Mn impurities in GaN is crucial, as Mn can exist in multiple charge states, influencing magnetic interactions.

GaN:Mn has been extensively studied using magnetometry techniques like SQUID to explore its magnetic properties. For example, magnetization measurements on highly resistive bulk GaN:Mn^{3+} have revealed strong magnetic anisotropy with significant zero-field splitting [1,2]. This zero-field splitting is so pronounced that it is undetectable by conventional EPR methods, often rendering the material "EPR-silent." However, EPR studies on GaMnN thin films have provided valuable insights into the local electronic structure of Mn ions and the spin Hamiltonian parameters [3].

Recently, we have developed uniqe high field/high frequency EPR ellipsometry to probe defects in wide and ultrawide band gap semiconductors, offering improved sensitivity and the ability to obtain the full polarization response of a sample [4,5]. In this work, we employ this new method using our state-of-the-art, in-house-built terahertz ellipsometer to investigate Mn-doped GaN single crystals. We have determined for the first time a zero-field splitting on the order of 200 GHz, explaining why Mn^{3+} was previously considered ‘EPR-silent’ by conventional EPR techniques. We have also obtained the spin Hamiltonian parameters for Mn^{3+} in GaN, providing insights into the charge state, local site symmetry, Jahn-Teller effects, and interactions with the local environment. Additionally, we establish the temperature dependence of the spin Hamiltonian parameters. These news insights advance our understanding of Mn impurities in GaN and open up opportunities for controlling electron spin.

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Ferroelectric nitrides

2025-07-08
10:30 - 12:00
Ferroelectric nitrides

PC-Tue-B6 - First-principles description of ferroelectric nitrides

2. Physics and characterization

Chris Van de Walle[1]
[1] Materials Department, University of California, Santa Barbara, USA

Abstract text: Polarization fields play a crucial role in nitride-based devices: sometimes as a nuisance (suppressing efficiency of light emitters), sometimes as a functional enhancement (increasing the density of two-dimensional carrier gases in transistors). Accurate knowledge of polarization constants is critical for analysis of experiments and for device design. Some years ago we identified deficiencies in the calculation of polarization fields in simulation tools, related to the choice of the zinc-blende phase as a reference for the spontaneous polarization of wurtzite [1]. However, since the current implementations contain *two* errors that to some extent cancel, most modeling has continued to use the zinc-blende-referenced approach. This has, unfortunately, led to major confusion in the analysis of polarization in AlScN alloys. Correct referencing of spontaneous polarization (relative to a layered-hexagonal phase) is essential for consistent interpretation of ferroelectricity in AlScN alloys [2]—and indeed for rigorous modeling of polarization in general.

I will describe how first-principles calculations based on the Modern Theory of Polarization provide a consistent framework for modeling polarization in alloys [3] and at interfaces [4]. In addition to AlScN, I will present for AlBN, and for LaN, a binary compound that is potentially ferroelectric [5].

Work performed in collaboration with Cyrus Dreyer, Haochen Wang, Zekun Wu, Andrew Rowberg, Suhyun Yoo, Mira Todorova, Jörg Neugebauer, and Simon Fichtner, and supported by SUPREME (SRC/DARPA), DOE, and ARO.

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PC-Tue-B7* - Phonons, Born effective charges, and band gaps of wz-(Sc,Al)N alloys (0 ≤ Sc ≤ 30%) grown on AlN/Si by molecular beam epitaxy

2. Physics and characterization

Jona Grümbel[1]
Duc V. Dinh[2], Christina Harms[1], Zhuohui Chen[3], Oliver Brandt[2], Rüdiger Goldhahn[1], Martin Feneberg[1]
[1] Otto-von-Guericke-Universität, Institut für Physik, Magdeburg, Germany
[2] Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., Berlin, Germany.
[3] Huawei Technologies Canada Co., Ltd., Kanata, Canada.

Abstract text: Research on wurtzite (wz) Sc*x*Al1-*x*N alloys is currently a topic of high interest due to their enhanced piezoelectricity and ferroelectricity, making them candidates for acoustic wave resonators in next generation 5G receivers and high electron mobility transistor (HEMT)structures. Although numerous devices are already fabricated and analyzed, the growth of single crystalline films is still not sufficient and fundamental physical processes, such as band gap bowing or phonon behavior, are not yet described adequately. We investigate single crystal wz-ScAlN layers (*c*-plane with ≈350 nm thickness) on AlN/Si templates grown by molecular beam epitaxy, which yields detailed insights into materials properties of wz-ScAlN alloys. Raman spectroscopy, infrared and near infrared to ultraviolet spectroscopic ellipsometry (IR-SE and UV-SE) are employed to determine phonon frequencies and band gaps. We find that the ordinary transverse optical (TO) phonon frequencies decrease linearly with increasing Sc content, which coincides with the linear decrease of the lattice parameter *a* measured by x-ray diffraction. High Sc-contents lead to increased and seemingly asymmetric broadening of the ordinary phonon resonance, which indicates the existence of a second phonon arising at higher alloy concentrations. We interpreted this as evidence of a 2-phonon behavior in wz-ScAlN alloys, similar to what has been previously observed in wz-AlGaN alloys, although it follows unclear trend. The dielectric loss function is indeed utilized to obtain the longitudinal optical (LO) phonon frequencies, where we can obtain both the ordinary and extraordinary LO-frequencies. The Born-effective-charges are calculated from the determined TO and LO-frequencies and correlated to the measured piezoelectric coefficient. Additionally, the optical constants of ScAlN layers are determined from UV-SE, where absorption edges are correctly derived using the inflection point method instead of the widely used Tauc-plot method. Utilization of the latter is dangerous in the vicinity of an indirect band gap and additional high alloy broadening, which appears at increasing Sc content. Thus, this method has to be avoided when absorption edges are derived in ScAlN alloys.

PC-Tue-B8 - Identification of scandium vacancies in scandium nitride single crystals

2. Physics and characterization
Filip Tuomisto[1]
Igor Prozheev[1], Hayder Al Atabi[2], James H. Edgar[2]
[1] Department of Physics, University of Helsinki, Helsinki, Finland
[2] Tim Taylor Department of Chemical Engineering, Durland Hall, Kansas State University, Manhattan, KS, USA

Abstract text: The shared common element and small lattice constant mismatch (0.4% with GaN) make scandium nitride (ScN) a logical material to combine with group III nitride semiconductors in alloys such AlScN, and in heterojunctions (e.g., GaN/ScN). In contrast to the group III nitrides, ScN has a cubic rock salt crystal structure, an indirect bandgap (E_g = 2.0), and high thermal stability. Interestingly, ScN has the propensity toward a large density of nitrogen vacancies [1].

The present study was undertaken to identify and quantify vacancy-type defects in ScN by positron annihilation spectroscopy [2]. The ScN crystals were grown by physical vapor transport (PVT), i.e., the sublimation of scandium metal at high temperature (~2000°C) in a nitrogen atmosphere, initially on a tungsten (100) single crystal seed [3]. PVT is able to grow thick (>1 mm), free-standing ScN crystals with the (100) orientation of the highest structural perfection, and free of contamination which is present with transporting agents. ScN crystals grown by PVT are n-type with an electron concentration of 2.2×10^{21} cm^{-3}, and a room temperature electron mobility of 73 cm2/V-s, and a thermal conductivity of 50 W/m-K [4].

The average positron lifetime measured at temperatures 200-600 K in the ScN crystals is constant at a value of 145 ps. When the temperature is decreased to 50 K, the average lifetime drops to 125 ps. The positron lifetime spectrum contains two components, of which the longer is roughly 250 ps. The temperature behavior of the positron lifetime is indicative of the coexistence of vacancy-type defects and negatively charged non-open volume defects (so-called negative ions). The relatively long vacancy-related lifetime component strongly suggests that the vacancy defects in question are Sc vacancies, possibly complexed with N vacancies. As the positron data further suggest the lattice lifetime of ScN to be 120-125 ps, the concentration of these Sc vacancies can be estimated as 5×10^{16} cm^{-3}. High-energy particle irradiation experiments are underway for more detailed identification of the vacancy-type defects in ScN.

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[2] F. Tuomisto and I. Makkonen, Rev. Mod. Phys. **85**, 1583 (2013).

[2] H. A. Al Atabi *et al.*, Appl. Phys. Lett. **113** 122106 (2018).

[3] H. Al-Atabi *et al.*, Appl. Phys. Lett. **116** 132103 (2020).

PC-Tue-B9* - X-ray Spectroscopic Characterization of Surface Oxidation of ScAlN Thin Films Grown by Sputtering on GaN

2. Physics and characterization

Hikaru Sasaki[1]
Akihira Munakata[2], Masaki Kobayashi[3], Ryota Yamamoto[4], Sawaki Sato[4], Atsushi Kobayashi[4], Takuya Maeda[1]
[1] Department of Electrical Engineering and Information Systems, The University of Tokyo, Tokyo, 113-8656, Japan
[2] Department of Electrical Engineering and Information Systems, The University of Tokyo, Tokyo, 113-8656, Japan
[3] Department of Electrical Engineering and Information Systems, The University of Tokyo, Tokyo, 113-8656, Japan, Center for Spintronics Research Network, The University of Tokyo, Tokyo 113-8656, Japan
[4] Department of Materials Science and Technology, Tokyo University of Science, Tokyo, 125-8585, Japan

Abstract text: ScAlN is attractive as a material for a barrier layer of a GaN HEMT, due to its wide bandgap, strong polarization and capability of epitaxial integration with GaN. The surface of ScAlN readily oxidizes in the atmosphere, which affects the structural and electrical properties [1]. In this work, we investigate the surface oxidation and chemical bonding states of ScAlN thin films grown by sputtering, utilizing X-ray photoelectron spectroscopy (XPS) and X-ray absorption spectroscopy (XAS) measurements.

Two thin films of (a) 57-nm-thick $Sc_{0.13}Al_{0.87}N$ and (b) 66-nm-thick $Sc_{0.27}Al_{0.73}N$ were epitaxially grown on GaN/sapphire substrates by sputtering [2, 3]. The samples were exposed to air after the growth. XPS and XAS measurements were performed at SPring-8 and KEK PF, respectively. For the XPS measurements, X-rays with photon energies of 850 eV and 1200 eV were used. Escape depths for 850 eV and 1200 eV are about 1 nm and 3 nm, respectively.

In the wide spectra of XPS, Al 2*p*, Sc 2*p* core-levels (CLs) and other reasonable peaks were observed. For the Al 2*p* CL spectra of the sample (a), the consistent tailing for higher binding energy is observed for each photon energy. For the sample (b), the peaks have larger tailing than that of (a), which increased as photon energy decreased. The Sc $2p_{3/2}$ CL spectra exhibited two peaks: the Sc-N peaks (Sc_N $2p_{3/2}$) and the Sc-O peaks (Sc_O $2p_{3/2}$) [1], and the intensities of Sc_O $2p_{3/2}$ peaks clearly increased for 850 eV for both (a) and (b). The peak ratio of Sc_O $2p_{3/2}$/Sc_N $2p_{3/2}$ significantly increased as the Sc composition increased. These results suggest that oxidation is mostly pronounced near the surface (~1 nm), and surface oxidation is enhanced as Sc composition increases.

The Sc-L_2 and Sc-L_3 edges XAS spectra of the samples (a) and (b) (measurement depth ~20 nm) exhibited the 4 distinct peaks, which reflect the transitions from Sc 2*p* to e_g and to t_2g orbitals in the octahedral (O_h) symmetry [4]. The intensity of the e_g peaks increased with increasing Sc composition. These results suggest that the oxidized ScAlN near the surface has the rock salt-like crystal structure, and the e_g orbitals contribute to surface oxidation.

[1] M. Li *et al*., *APL* **121**, 111602 (2022). [2] A. Kobayashi *et al*., *APEX* **17**, 011002 (2023). [3] T.

Maeda *et al*., *APL* **125**, 022103 (2024). [4] B. Biswas *et al*., *J. Vac. Sci. Technol. A* **38**, 053201 (2020).

PC-Tue-B10 - Electrical properties of CrN layers grown on AlN templates with different surface orientations by plasma-assisted molecular beam epitaxy

2. Physics and characterization
Duc Van Dinh[1]
Jens Herfort[1], Oliver Brandt[1]
[1] Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., Hausvogteiplatz 5–7, 10117 Berlin, Germany

Abstract text: CrN is an emerging group-III_B transition-metal nitride semiconductor due to its unique combination of mechanical, electronic, thermoelectric, and magnetic properties. The electronic structure of CrN, particularly its bandgap, remains a subject of ongoing debate, with reported values ranging from 0.02 to 0.09 eV depending on the measurement technique and sample quality. It is important to note that the electrical bandgap of CrN is most commonly estimated through temperature-dependent resistivity measurements, rather than through direct electrical measurements of the carrier concentration obtained by temperature-dependent Hall-effect measurements [1,2]. This reliance on resistivity data can introduce uncertainties in the determination of the bandgap, as it may not accurately reflect the intrinsic electronic properties of this material.

Here, we report on the growth and electrical properties of 75-nm-thick nominally undoped CrN layers grown simultaneously on AlN(0001)/Al_2O_3(0001) and AlN(11-22)/Al_2O_3(10-10) templates using plasma-assisted molecular beam epitaxy. High-resolution x-ray diffractometry reveals that the layer grown on AlN(0001) has a pure (111) surface orientation, while the layer on AlN(11-22) exhibits a pure (113) orientation. The electrical properties of these layers have been investigated by Hall-effect measurements performed in the van der Pauw configuration. Measurements at room temperature indicate that the CrN(111) and CrN(113) layers have electron densities of 2.3×10^{19} cm^{-3} and 2.7×10^{19} cm^{-3}, with corresponding mobilities of 19 $cm^2V^{-1}s^{-1}$ and 12 $cm^2V^{-1}s^{-1}$, respectively. Temperature-dependent Hall-effect measurements from 4 to 400 K indicate that both layers exhibit semiconducting behavior. Additionally, these measurements clearly reveal a Néel temperature of about 280 K, confirming the antiferromagnetic nature of CrN. Leveraging knowledge from another transition-metal nitride, ScN [3], we thoroughly investigate the electrical properties of the CrN layers. We found that the layers exhibit a two-band conduction mechanism with an electrical bandgap of (0.23 ± 0.01) eV.

[1] Q. Jin et al., Phys. Rev. Mater., **5**, 023604 (2021).

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InGaN for full visible LEDs

2025-07-08
10:30 - 12:00
InGaN for full visible LEDs

GR-Tue-6 - Growth integration of InGaN-based full visible LEDs

1. Growth

Mitsuru Funato[1]
Yoshinobu Matsuda[1], Yoichi Kawakami[1]
[1] Kyoto Univesity, Kyoto, Japan

Abstract text: Micro/Nano-LED displays are an emerging device for a next generation data presenting tool. LEDs have advantages such as high brightness and consequent low energy consumption but suffer from assembly yields and costs. One of the reasons is a technical difficulty of mass transfer of element micro/nano-LEDs into display pixels. To overcome this issue, epitaxial growth integration of element LEDs, instead of mass transfer, is promising. We have recently demonstrated that three dimensional (3D) structures can be formed through photolithography followed by reactive ion etching (RIE) and can offer opportunities to realize such growth integration.

GaN layers were grown on sapphire (0001) substrates by metalorganic vapor phase epitaxy (MOVPE). On top of GaN, photoresist was deposited and was transformed into 3D structures through gray-scale- or (conventional) photo-lithography with a thermal reflow technique: the former can produce polyhedral microstructures, while the latter can produce micro lens-shaped structures. Then, the 3D structure of the photoresist was transferred into the GaN layer by RIE. Interestingly, the inclination angles of the surfaces of those 3D structures are controllable by adjusting the process conditions, which makes striking contrast to the case of the 3D structures formed with selective area growth. InGaN quantum well (QW) emitters were subsequently grown on the GaN 3D structures by MOVPE. Depending on the inclination angles of the underlying GaN surfaces, InGaN QWs have different In compositions and thicknesses. The controllability of the surface inclination angle leads to the controllability of the QW parameters and, consequently, the emission wavelength.

Examples of the fabricated structures include (a) microlens-like structures of which the emission spans the full visible region, (b) self-alignment of micro-LEDs emitting purple to green spectra on a stripe with a microlens-like cross section, and (c) integration of multicolor LEDs (or QWs) on the slopes of polyhedral structures. We demonstrated that separately formed multiple electrodes on those 3D structures enabled external control of the emission spectrum, suitable for display applications. In the presentation, we will discuss the status and remaining issues of our proposed methods.

GR-Tue-7 - Red emitting full InGaN micro-light emitting diodes grown on GaN mesas on Si substrate for monolithic Red-Green-Blue micro-displays

1. Growth

Amélie Dussaigne[1]
Julien Bosch[1], Guillaume Veux[1], Frédéric Barbier[1], Florian Fedeli[1], Bernard Aventurier[1], Eduardo Zatterin[2], Simona Torrengo[1], Tobias Schulli[2], Patrice Gergaud[1], David Cooper[1], François Lévy[1]
[1] Univ. Grenoble Alpes, CEA, Leti, F-38000 Grenoble, France
[2] ESRF- The European Synchrotron, Beam line ID01, F-38000 Grenoble, France

Abstract text: Full color micro-displays with a pixel pitch below 10 µm are needed for augmented reality. The InGaN alloy should be used to obtain the three primary colors in a monolithic integration. When grown on GaN, the $In_xGa_{1-x}N$ alloy is submitted to an important compressive strain and is known to strongly degrade for a high InN mole fraction. As an In content of 40% is needed for an efficient red emission, the strain should be reduced in the whole LED structure by using a relaxed InGaN pseudo-substrate combined with a full InGaN structure. We have already demonstrated red emitting InGaN/InGaN quantum wells (QWs) with an In content up to 40% on different InGaN pseudo-substrates[1,2]. Another approach is the growth of the full InGaN structure on GaN mesas which is compatible with a Red-Green-Blue (RGB) monolithic integration. Indeed, successive epitaxies can be employed to grow by selective area growth a first blue light emitting diode (LED) on GaN mesas, then a green one, and finally a red LED structure. 3,5 µm diameter blue and green full InGaN micro-LEDs grown on the same 200 mm Si substrate was already demonstrated[3]. For red emission, a relaxed InGaN buffer is necessary to get a high In incorporation rate. In addition, the adatom diffusion length has to be managed to get the desired LED structure on mesa top.

An in-plane lattice parameter of 3.212 Å was obtained on 3 µm diameter InGaN/GaN mesas, which is enough to enhance the In incorporation rate in the red QWs. Even on 10 µm diameter InGaN/GaN mesas, the in-plane deformation is significant and homogeneous from the centre to near the edges of the mesas[4]. Plastic relaxation through the formation of misfit dislocations at the InGaN/GaN interface is probably at play. Structural investigations are on going.

Depending on the mask design, the In incorporation rate varies. It is directly linked to the In adatom diffusion length. The QW epitaxy sequence was then modified in order to improve the residence time of In adatoms on mesa top. After a first optimization, an homogeneous red emission centered at 610 nm was obtained on 4 µm diameter InGaN/GaN mesas with a 5 µm pitch on Si. The next step will be the realization of RGB full InGaN micro-LEDs grown on the same 200 mm Si substrate.

[1]Appl. Phys. Express 14, 092011 (2021)
[2]Com. Materials 5, 280 (2024)
[3]M. Charles *et al.*, ICNS-14
[4]Phys. Stat. Sol. RRL 2400241 (2024)

GR-Tue-8* - Growth of Highly Relaxed (In,Ga)N Pseudo-Substrates with a Smooth Surface by a Continuous Three-Step Protocol without Ex-situ Patterning

1. Growth

Huaide Zhang[1]
Jingxuan Kang[1], Oliver Brandt[1], Lutz Geelhaar[1]
[1] Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., Hausvogteiplatz 5-7, 10117, Berlin, Germany

Abstract text: Micro-light emitting diodes (μ-LEDs) have garnered significant attention in virtual reality and display technologies. Current μ-LED products predominantly utilize blue and green (In,Ga)N LEDs alongside red arsenide/phosphide LEDs. However, the differences in thermal and chemical stability between these material systems present challenges for LED integration.

Red (In,Ga)N LEDs are considered a promising alternative. Yet, the large lattice mismatch between the GaN substrate and the active region with around 40% In content introduces strong strain, leading to reduced quantum efficiency. Thus, (In,Ga)N pseudo-substrates containing around 25% In with high strain relaxation are proposed for high-performance red (In,Ga)N LEDs.

In this study, we present a three-step protocol for fabricating relaxed (In,Ga)N pseudo-substrates on GaN(0001) templates, which is conducted entirely within a plasma-assisted molecular beam epitaxy system without ex-situ patterning. The key concept is to grow firstly a rough GaN layer under N-rich conditions, then introduce In still under N-rich conditions to form (In,Ga)N nanowires (NWs), and ultimately coalesce these NWs into a smooth layer under metal-rich conditions.

The rough GaN layer exhibits a spotty reflection high energy electron diffraction (RHEED) pattern. In is then gradually introduced to achieve the targeted In content in NWs. During the coalescence step, the RHEED pattern transitions from spotty to streaky and eventually shows a reconstruction. Surface morphology analysis using scanning electron microscopy and atomic force microscopy reveals a fully coalesced layer with a root mean square roughness of 2.3 nm. X-ray diffraction reciprocal space mapping around the 105 reflection indicates a strain relaxation degree of 80% and In content of 27%. The photoluminescence spectrum presents an emission band centered at 536 nm, corresponding to 24% In.

In conclusion, we have developed a straightforward and scalable method for the growth of relaxed (In,Ga)N layers with a target indium content of around 25%, smooth surfaces, and high strain relaxation. Unlike other techniques requiring specialized etching steps to create pseudo-substrates, this three-step growth protocol is cost-effective, simple, and compatible with large-scale production that holds significant potential for advancing red (In,Ga)N LEDs in μ-LED applications.

GR-Tue-9 - AlScN pseudo-substrates for lattice matched InGaN epitaxy

1. Growth

Jörg Schörmann[1]
Silas A. Jentsch[1], Mario F. Zscherp[1], Markus Stein[1], Florian Meierhofer[2], Christoph Margenfeld[2], Andreas Waag[2], Sangam Chatterjee[1]
[1] Institute of Experimental Physics I and Center for Materials Research, Justus-Liebig-University Giessen, Giessen, Germany
[2] Institute of Semiconductor Technology and Nitride Technology Center, Technische Universität Braunschweig, Braunschweig, Germany

Abstract text: In recent years, (Al,Sc)N has emerged as a subject of intense research interest, particularly within the domain of semiconductor electronics and optoelectronics. Scandium nitride is a transition metal nitride semiconductor. One of its remarkable properties, besides high hardness, high melting point high electron mobility and high electro-optical coefficients, is the tunability of the lattice constant in a wide range.

The fabrication of high-quality quaternary AlInGaN, e.g., for heterostructures lattice-matched to GaN, is particularly difficult due to the drastic differences between InN and AlN/GaN in bond strength, resulting in very different optimized growth temperatures.

AlScN is a promising candidate to help overcome these limitations, since AlScN has a large growth temperature window that is compatible with high-quality AlGaN epitaxy. Therefore, pseudo-substrates for the growth of lattice matched InGaN can be envisioned by modifying the in-plane lattice parameter of AlScN.

In this study, we employ conventional MOCVD-made GaN-on-sapphire as substrate for MBE-grown AlScN and compare as-grown surfaces without and with subsequent InGaN cappings. After surface preparation (heating, degreasing), a GaN layer has been deposited for two hours at T=720 °C. AlScN layers with different Sc concentrations are grown by molecular beam epitaxy for 30 minutes in N-rich growth conditions [1,2]. Samples are subsequently overgrown by InGaN with layers with a thickness of ~100 nm. An improved lattice matching due to AlScN pseudo-substrates leads to an improved structural quality of InGaN. MBE growth was monitored *in situ* by reflection high-energy electron diffraction (RHEED). High-resolution X-ray diffraction (HRXRD) provides structural insights like phase purity, layer quality, strain and lattice constants. Atomic force microscopy (AFM) of the InGaN indicates smooth surfaces with RMS ~1.6 nm. Photoluminescence (PL) studies reveal the optical response of the grown structures, while microscopic features are resolved by cathodoluminescence (CL) hyperspectral imaging. The potential of AlScN as a pseudo-substrate for lattice-matched InGaN with high Indium content will be discussed.

[1] M. T. Hardy et al., IEEE Trans. Semicond. Manuf. 30, 475-479 (2017)

[2] J. Casamento et al., Apl. Phys. Lett. 117, 112101 (2020)

GR-Tue-10 - Advanced High-Flow-Velocity Horizontal MOCVD Technology for Nitride Semiconductor Growth

1. Growth

Keitaro Ikejiri[1]
Yudai Shimizu[1], Mizuki Yamanaka[1], Kenichi Eriguchi[1], Kazutada Ikenaga[1], Hiroki Tokunaga[1]
[1] TAIYO NIPPON SANSO Corporation, 10 Okubo, Tsukuba, Ibaraki 300-2611 Japan

Abstract text: The expansion of nitride semiconductor applications, such as LEDs, lasers, and high-power electronics, requires MOCVD systems that can precisely control crystal growth while maintaining high throughput. In this context, the MOCVD process has conflicting requirements. For high-quality GaN or high-indium-content InGaN deposition, relatively high pressures are necessary. However, increasing pressure leads to enhanced parasitic growth, resulting in deteriorated crystal quality and uniformity. Conversely, lower pressures improve the thickness and composition uniformity of AlGaN and control the carbon concentration in GaN. The optimal MOCVD system for flexible control of nitride semiconductors must handle pressures from low to atmospheric while maintaining high-flow velocities through narrow channels. The challenge is to meet these requirements effectively in both R&D and mass production. Taiyo Nippon Sanso's MOCVD system achieves this with a high-flow-velocity system using triple gas injectors in a horizontal reactor with a flow channel height under 10 mm, and a gas control system operating from low to atmospheric pressure. In addition, zone-divided resistive heating technology allows the system to accurately regulate temperatures even for large diameter wafers as well as wafers that deform into concave or convex shapes during high-temperature processes.

The system's effectiveness was demonstrated with AlGaN growth. Using the SR4000 MOCVD system for a single 4-inch substrate, we controlled the Al composition in AlGaN by adjusting the TMA to total MO supply ratio (TMG + TMA) linearly. This method maintained a favorable Al composition distribution (in-plane max-min ≤ 1.5%) and thickness distribution (in-plane max-min/average < 5.0%) for 40% to 80% Al composition. The same approach applies to the UR26K MOCVD system, a large-scale production system for 6 x 8-inch substrates. Optimizing growth conditions achieved an Al composition distribution (in-plane and inter-plane max-min ≤ 0.2%) and thickness distribution (in-plane and inter-plane max-min ≤ 1.0 nm, average: 18.1 nm) in the AlGaN barrier layer of AlGaN/GaN HEMT on Si. We will also discuss the flow channel effectiveness using numerical simulations and InGaN crystal growth characteristics.

Far-UVC LEDs: size-dependence and polarization doping

2025-07-08
10:30 - 12:00
Far-UVC LEDs: size-dependence and polarization doping

OD-Tue-6 - Growth of UVC LEDs and lasers

3. Optical devices

Tim Wernicke[1]
[1] Technische Universität Berlin, Institute of Solid State Physics, 10623 Berlin, Germany

Abstract text: AlGaN-based UVC light emitting diodes (UVC-LEDs) near 265 nm are on the verge of replacing mercury discharge lamps for water, air and surface disinfection. Far-UVC LEDs (<240 nm) have already shown great promise in skin-safe inactivation of multidrug-resistant pathogens. UVC-LEDs in the disinfection band between 250 nm and 280 nm exhibit high output powers and lifetimes exceeding 10.000 hours, whereas at shorter UVC wavelength the external quantum efficiencies (EQE) and lifetimes rapidly deteriorate. AlGaN-based UVB and UVC edge-emitting laser diodes are still in their early development phase, but exciting concepts for vertically emitting UVC lasers have recently been demonstrated.

In particular, photonic crystal surface emitting lasers (PCSELs) and vertical surface emitting lasers (VCSELs) offer high beam quality with a narrow far-field. For PCSELs a nanometric sized hole pattern is etched into the device. Overlap of the optical mode with the quantum wells and the photonic crystal as well as the detuning to the gain peak are important for low lasing thresholds which are in the range of 3 MW/cm² under optical pumping. To realize VCSELs we remove the substrate by photoelectrochemical etching to realize dielectric high reflectivity mirrors on both sides of the cavity yielding optically pumped lasing thresholds < 0.5 MW/cm², thanks to an accurate control of the detuning. Both laser concepts are promising but the transfer into electrically driven devices is very challenging.

A key technology to realize electrically driven laser diodes and efficient UVC LEDs is distributed polarization (DPD) p-type doping. It allows us to achieve high hole densities and conductivity for layers with high aluminum mole fraction beyond 70%. Comparing the operation voltages of LEDs with and without DPD layers, we found no significant increase up to a DPD layer thickness of 320 nm, which is in contrast to Mg doped $Al_{0.68}Ga_{0.72}N$ layers where > 20 V are reached for just 200 nm thick layers. CV-measurements show “acceptor” densities > $5x10^{17}$ cm^{-3} depending on the Al content gradient in agreement with theoretical calculations. Also, DPD-LEDs are stable at high current density > 80 kA/cm^2 – making the DPD suitable for laser diode operation.

In summary I will discuss the roadmap to achieve advanced UVC LEDs and laser diodes, including the analysis of their internal efficiency parameters.

OD-Tue-7 - Size-Dependent Efficiency in UVB and Far-UVC µLEDs probed by Cathodoluminescence

3. Optical devices

Gwenole JACOPIN[1]
Jens Rass[2], Tim Kolbe[2], Sven Einfeld[2]
[1] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France
[2] Ferdinand-Braun-Institut (FBH), Gustav-Kirchhoff-Str. 4, 12489 Berlin, Germany

Abstract text: Far ultraviolet (UV)-C (<240 nm) light-emitting diodes (LEDs) are gaining increasing interest for disinfection applications. However, their efficiency remains low (<2%) compared to blue and UV-C LEDs, partly due to limited light extraction. Recently, µLEDs have been shown to significantly enhance extraction efficiency in this specific spectral region [1]. Surprisingly, the external quantum efficiency (EQE) increases as the µLED diameter decreases, even down to 1.5 µm, contrary to the trend observed in blue µLEDs, where EQE drops due to non-radiative surface recombination [2].

To understand this unexpected behavior, we studied two µLED structures grown by MOVPE on sapphire. The first targets the UVB region (~310 nm) with an $Al_{0.24}Ga_{0.76}N/Al_{0.32}Ga_{0.68}N$ multi-quantum well (MQW) active region. The second is designed for far-UVC emission (~235 nm) with an $Al_{0.72}Ga_{0.38}N/Al_{0.83}Ga_{0.17}N$ MQW active region. The µLED structures were etched following the process described in Ref. [1]. To probe the optical properties of these µLEDs at the nanoscale, we performed time-correlated cathodoluminescence (CL) spectroscopy. This technique provides <50 nm spatial and <30 ps temporal resolutions [3].

First, for UVB µLEDs, we observed strong carrier localization that prevents carriers from reaching etched surfaces where they would potentially recombine non-radiatively through surface recombinations. Accordingly, the CL lifetime varies from 500 ps in localized centers to 100 ps elsewhere, with a positive correlation between CL intensity and lifetime, indicating defect density variations across the µLED. For far-UVC µLEDs, we observed that the overall CL intensity increased with decreasing size, consistent with the improved light extraction observed in electrically injected devices. CL energy mapping showed a blueshift near etched surfaces, attributed to strain relaxation. In contrast to blue µLEDs [2], the lifetime increases near the edges, which could possibly result from strain relaxation. The extremely short lifetime (80–180 ps) suggests a short carrier diffusion length, which could explain why surface recombination at the mesa edge does not represent a considerable loss channel in UVC LEDs.

[1] J. Rass *et al.*, Appl. Phys. Lett. 122, 263508 (2023)

[2] S. Finot *et al.*, ACS Photonics 9, 173 (2021)

[3] P. Sáenz de Santa María Modroño *et al.*, ACS Photonics 11, 2406 (2024)

OD-Tue-8 - Effect of thickness and composition gradient in the polarization doping layer of 226 nm far-UVC light emitting diodes

3. Optical devices

Tim Kolbe[1]
Sylvia Hagedorn[1], Jens Rass[1], Hyun Kyong Cho[1], Sven Einfeldt[1], Markus Weyers[1]
[1] Ferdinand-Braun-Institut (FBH), Berlin, Germany

Abstract text: AlGaN-based far-ultraviolet-C (far-UVC) light emitting diodes (LEDs) ($\lambda < 240$nm) are effective and beneficial light sources for skin-safe disinfection, particularly for the eradication of multi-drug-resistant germs, as well as for gas sensing (e.g. NO, NH_3).

The use of a polarization doping layer (PDL) is an effective solution to achieve a reasonable hole injection into the active region of far-UVC LEDs. In this study 226nm far-UVC LEDs with different thicknesses and AlGaN composition gradients in the PDL are compared w.r.t. their electro-optical characteristics and lifetimes. The heterostructures were grown by metalorganic vapor phase epitaxy on double growth and double annealed AlN/sapphire templates. In a first experiment LEDs with a constant PDL thickness of 100nm and different PDL composition gradients were compared. Therefore, we changed the Al mole fraction during growth of the PDL linearly from the start value 1 to the end values 0.8, 0.75, 0.5 and 0.2. Electroluminescence measurements of front-end processed wafers show a slight increase of emission power (EP) with decreasing Al mole fraction for end values from 0.8 to 0.5. However, a further reduction to 0.2 leads to a significant reduction in EP at 50mA from 0.2mW to only 0.03mW (on-wafer). In a second series, LEDs with the same slope in the PDL but with different thicknesses of the PDL (from 80nm to 320nm) are compared. In this case LEDs with a PDL thickness larger than 100nm show an increase of operation voltage and a decrease of EP which can be explained by a reduced hole injection into the active region. The LED with the thickest PDL of 320nm does not shows any luminescence. Lifetime measurements show a 3-times higher L70-lifetime for the best sample.

To explain the changes in EP, voltage, and lifetime we will present a detailed analysis of the electro-optical characteristics of the different LEDs and correlate this with simulations of the LED heterostructure. This will make it possible to set clear design parameters for a p-side with an efficient hole injection into the active region of far-UVC LEDs.

Finally, selected LED chips were flip-chip-mounted on planar AlN ceramic submounts and measured in an integrating sphere (cw, at 20°C). A peak external quantum efficiency, peak wall plug efficiency, voltage, and EP at 200mA of 0.3%, 0,2%, 9.6V, and 2.1mW, respectively, were determined.

OD-Tue-9 - A 265 nm Deep-Ultraviolet Micro-Light-Emitting Diode Array with Emission Areas of Less than 10 μm in Diameter

3. Optical devices

Yuma Yamaguchi[1]
Shigeya Kimura[1], Tetsuya Miyagawa[2], Rei Hashimoto[2], Shinji Saito[2], Shinya Nunoue[1]
[1] Corporate Research and Development Center, Toshiba Corporation, Kawasaki, Kanagawa, Japan
[2] Corporate Manufacturing Engineering Center, Toshiba Corporation, Isogo-ku, Yokohama, Japan

Abstract text: We developed deep-ultraviolet (UV) micro-light-emitting diode (LED) arrays with emission areas of less than 10 μm in diameter. The external quantum efficiency (EQE) of the LED array with emission areas of 2 μm in diameter reached 8.5 % emitting at a wavelength of 265 nm. For AlGaN-based UV-LEDs of conventional size, the EQE decreases with decreasing wavelength. This is due to an increase in the transverse-magnetic polarized light component and a decrease in light extraction efficiency, as well as a decrease in current spread due to higher resistance. Improvement of these issues can be expected by miniaturizing and arraying the LED elements. The EQE of LEDs with emission wavelength of around 280 nm has been reported to reach 20%, while the efficiency of LEDs with wavelength below 265 nm is about 8% at best. We aim to improve the efficiency of UV-LEDs of wavelength 265 nm, which is considered effective for sterilization, by further miniaturization of the abovementioned micro-LEDs.

AlGaN-based UV-LED layers were grown on Al_2O_3(0001) by metal–organic chemical vapor deposition. Deep-UV micro-LED arrays of 16 × 16 and 32 × 32 with 24 μm pitch were fabricated with devices separated by 2 μm in diameter. To compare the effect of device miniaturization, micro-LED arrays with emission areas 4, 6, and 8 μm in diameter per element were also fabricated. In each device, n-type and p-type electrodes were individually connected by p-metal and n-metal narrow wires, respectively. We confirmed that the light emitted from all elements at emission peak of 265 nm without abnormality in the micro-LED arrays. EQE versus current density curves for the micro-LED samples with the emission areas of 2 and 6 μm in diameter revealed that the EQE of micro-LED arrays with 2 μm mesa reached 8.5 % at highest and was higher than that of 6 μm mesa throughout the entire range. This is attributed to the finer separation of micro-LEDs, which increases the light extraction at the mesa edge surface. Another reason is that the current density uniformity per array can be improved by limiting the areas where the current does not flow, which is a problem with large-area LEDs.

OD-Tue-10 - Far-UVC micro LED arrays for efficient light extraction and fiber coupling

3. Optical devices

Jens Rass[1]
Martin Guttmann[1], Hyun Kyong Cho[1], Christoph Stölmacker[1], Tamukanashe Anthony Musengezi[1], Jan Ruschel[1], Tim Kolbe[1], Sven Einfeldt[1]
[1] Ferdinand-Braun-Institut (FBH)

Abstract text: Far-UVC light emitting diodes (LEDs) ($\lambda \leq 235$ nm) can be used for applications such as sensing of gasses (e.g. NO) or the skin-safe eradication of pathogens, of which many require fiber coupled sources. Their widespread use has been hampered so far by the devices' low efficiencies, which are in the range of a few percent. One of the main obstacles in achieving high power and highly efficient far-UVC LEDs is their low light extraction efficiency (LEE), since a large part of the generated photons, in particular the laterally emitted transverse magnetic (TM) polarized photons, are trapped inside the chip and subsequently absorbed. Furthermore, the light is emitted in a wide angle from the chip's backside and its sidewalls. The low LEE, the wide emission angle, and the narrow acceptance angle of UV-transparent fibers (NA = 0.22) makes it inefficient to couple the light into fibers.

One effective way to increase the LEE and thus the external quantum efficiency (EQE) is to use arrays of micro LEDs with small diameters and approximately 45° inclined and reflective mesa sidewalls to redirect the TM polarized photons towards the chip backside. Using this approach, the LEE could be increased by a factor of 2-3 and peak EQEs of up to 2.7 % at 234 nm emission wavelength were demonstrated [1].

Another advantage of this approach is the reduction of the far field emission angle, which together with the higher LEE increases the power that can be coupled into optical fibers. We studied quartz fibers with diameters of 400, 600, and 910 µm as well as a bundle of 7 x 500 µm fibers, and measured the optical power from conventional far-UVC LEDs and micro LED arrays transmitted in the fibers. The transmitted power increases both with increasing fiber diameter and decreasing pixel diameter, without any advantage from the fiber bundle. The transmitted power through a 910 µm fiber from a 234 nm LED operated at 20 mA increased from 13 µW for a conventional large area LED to 55 µW for a 1.5 µm micro LED array. While a large part of this enhancement is due to the increased LEE, the smaller far field emission angle further increases the transmission efficiency (transmitted power vs. overall emitted power), reaching 5.6 % for the 1.5 µm micro LED array as compared to only 3 - 4 % for the large area chips into a 910 µm fiber.

1) J. Rass et al., Semicond. Sci. Technol. **40** 015019 (2025)

Power Electronics 1 (Enhanced Performance)

2025-07-08
13:30 - 15:00
Power Electronics 1 (Enhanced Performance)

ED-Tue-11 - The Status of AlN Electronics and Optoelectronics Including the Important Role of Alternative Synthesis

4. Electronic devices

W. Alan Doolittle[1]
Habib Ahmad[1], Sangho Lee[1], Emily N. Marshall[1], Paul-Stephen Hutchinson-Maltaghati[1]
[1] Georgia Institute of Technology, School of Electrical and Computer Engineering

Abstract text: AlN is an emerging semiconductor that can offer dramatic and short-term exploitation in power switching, high temperature electronics, RF electronics and optoelectronics facilitated by breakthroughs in doping technologies enabled by low temperature, non-equilibrium epitaxy. Defect and impurity compensation can be reduced by controlling the surface chemistry with lower compensating vacancy concentrations being a key driver for lower temperature growth. Contrary to common understanding, low-temperature, metal-rich vacuum processes are shown to have higher diffusion lengths than high temperature nitrogen-rich methods. This feature can be utilized to inhibit silicon-DX center formation without compromises in crystal quality. First principles calculations identify the valence split off band as the dominant hole band, and because of its anomalous position above the heavy and light hole bands, an impurity band forms at dopant concentrations similar to GaN even with a deeper isolated acceptor energy. This anomalous band structure facilitates hole mobilities that are substantially higher than possible with GaN. AlN hole concentrations of ~4.4×10^{18} cm^{-3} and 0.045 W-cm resistivity, and electron concentrations of ~6×10^{18} cm^{-3}, and ~0.02 W-cm resistivity are shown and offer substantial promise for future generations of AlN bipolar electronic and optical devices.

ED-Tue-12* - GaN 650 V single-reference p-GaN bidirectional switch

4. Electronic devices

Giulio Baratella[1]
Urmimala Chatterjee[2], Olga Syshchyk[2], Stefaan Decoutere[2], Benoit Bakeroot[1]
[1] CMST (Ghent University), Technologiepark - Zwijnaarde 126, 9052 Ghent, Belgium; imec vzw, Kapeldreef 75, 3001 Leuven, Belgium
[2] imec vzw, Kapeldreef 75, 3001 Leuven, Belgium

Abstract text: Bidirectional switches (BDSs) are transistors that can conduct the current and block the voltage in both polarities, contrary to traditional transistors that only works in one direction. Traditional implementation of BDSs, such as anti-series, anti-parallel or diode-bridge BDSs, can be realized with gallium nitride (GaN) high-electron-mobility transistors (HEMTs), however, they do suffer from the same weaknesses as their silicon counterparts: they require a complex GaN-IC process flow to integrate the diodes, and they suffer from a voltage offset caused by the turn-on voltage of the diodes. The most promising BDS topology for GaN is the dual-gate p-GaN BDS, which, however, still requires two gate drivers to be operated.
The single-reference BDS is a bidirectional switch that only requires one gate driver and can be fabricated using the same GaN discrete process flow of the HEMT. It has been fabricated in imec's 650 V GaN technology on a 200 mm SOI substrate, featuring two p-GaN gates (controlled together) to reach normally OFF behaviour and 4 metal field-plates (FPs) at gate and reference contacts to spread the electric field during OFF-state operation and protect the gates. The device has been designed with multiple variations of the channel length and reference-connected field-plate design, and targets an operating OFF-state voltage of 650 V.
On-wafer measurements are performed using a Keysight B1505A power device analyser. The gates are controlled via a dedicated driver board which has been designed in-house around a commercial GaN HEMT gate driver for half-bridge applications. Results show good performance in both operating directions, with a symmetric resistance in ON-state (R_{ON}) as low as 22 Ωmm for a channel length of 24 µm, OFF-state leakage current of ~20 nA/mm at ±650 V and a hard breakdown voltage of that exceed 1 kV for positive polarization and -800 V for negative polarization. The hard breakdown is limited by the field-plate configuration for negative bias. The threshold voltage (V_{TH}) is equal to 2.5 V, in line with the V_{TH} of the HEMT realized with the same process flow. Preliminary high-temperature reverse-bias (HTRB) stress are also performed for 10 ks at 650 V and 150 °C, showing a degradation of the R_{ON} always lower than 13%.

ED-Tue-13 - A 650 V GaN Monolithic Integration Platform Featuring Low Capacitance and High-Performance Passive Components

4. Electronic devices

Yanlin Wu[1]
Junye Wu[1], Chao Feng[1], Danfeng Mao[1], Yu Shi[1], Xuan Liu[1], David Zhou[1], Yuxi Wan[1]
[1] Shenzhen Pinghu Laboratory, Shenzhen, China

Abstract text: Compared to traditional discrete implementations, monolithic integration effectively reduces interconnect parasitic effects, enabling higher operating frequencies. Additionally, the minimized output capacitance of power devices contributes to reduced switching losses. This paper presents a 650 V GaN integration platform developed by PH Laboratory. The 650 V GaN HEMT on this platform exhibits 50% lower $C_{iss}/C_{oss}/C_{rss}$ (111 pF/26 pF/0.8 pF at V_{DS} = 400 V, f = 100 kHz) compared to commercial 650 V GaN HEMTs [1]-[2], significantly reducing switching losses. The E-HEMT achieves V_{TH} = 1.3 V, R_{ON} = 10.8 Ω·mm and a breakdown voltage of 843 V at I_D = 1 μA/mm.

The platform provides a comprehensive passive component library comprising five key elements: MIM capacitors, M/2DEG capacitors, p-GaN capacitors, 2DEG resistors, and metal resistors. Characterization of 2DEG resistors reveals 0.38 Ω·mm contact resistance and 347.5 Ω/sq sheet resistance measured via transfer length method (TLM), complemented by metal resistors with 17 Ω/sq sheet resistance. This wide resistance range (347.5 Ω/sq vs. 17 Ω/sq) accommodates diverse circuit requirements while eliminating area inefficiencies caused by repeated winding in traditional designs. For capacitive components, the p-GaN stack capacitor achieves 111 nF/cm² at 6 V bias with an effective oxide thickness (EOT) of 37 nm, reaching a maximum density of ~162 nF/cm². This high capacitance density directly reduces capacitor footprint, optimizing layout area. Additionally, MIM capacitors attain 20 nF/cm² and M/2DEG capacitors reach 13.1 nF/cm², matching industry-reported benchmarks [3] while enhancing design flexibility through process co-integration.

[1] GS66508B Datasheet, GaN Systems, Ottawa, ON, Canada, 2020. [Online]. Available: https://www.gansystems.com. [2] SGT65R65AL Datasheet, STMicroelectronics, Geneva, Switzerland, 2023. [Online]. Available: www.st.com. [3] X. Li et al., "GaN-on-SOI: Monolithically integrated all-GaN ICs for power conversion," in *IEDM Tech. Dig.*, San Francisco, CA, USA, Dec. 2019, pp. 4.4.1–4.4.4, doi: 10.1109/IEDM19573.2019.8993572.

ED-Tue-14* - High Al-content AlGaN channel HEMTs with high current density

4. Electronic devices

Hridibrata Pal[1]
John Niroula[1], Ronald Green[2], Mihee Ji[2], Aivars Lelis[2], Tomas Palacios[1]
[1] Microsystems Technology Laboratories, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A
[2] DEVCOM Army Research Laboratory, Adelphi, MD 20783, U.S.A

Abstract text: Power amplifiers for upcoming mm-wave 5G and 6G networks must achieve exceptional performance in terms of power density, gain, efficiency, and linearity. While GaN-based High Electron Mobility Transistors (HEMTs) have shown strong capabilities, ultra-wide bandgap semiconductors like AlGaN may offer further enhancements. Thanks to their higher breakdown electric field (greater than 8 MV/cm), AlGaN materials are expected to provide a superior Johnson figure of merit, resulting in higher power densities and efficiencies at mm-wave frequencies.

Here, we have demonstrated an $Al_{0.7}Ga_{0.3}N$-channel HEMT with a doped $Al_{0.85}Ga_{0.15}N$ barrier. The epitaxial structure was grown by MOCVD on two different substrates: sapphire and AlN for comparison. A doped graded $Al_xGa_{1-x}N$ ($x = 0.85 \rightarrow 0.3$) layer was grown on top of the barrier to ease the formation of ohmic contacts.

The devices were fabricated with Ti/Al/Ni/Au contacts, annealed at 875 °C in a N_2 environment. The graded layer was etched away under the gate using reactive-ion-etching and Ni/Au gates were deposited. A contact resistance of ~8 Ω·mm was measured in devices on both substrates. Sheet resistance of 10 kΩ/□ and 6 kΩ/□ were extracted from transfer length method (TLM) measurements for the channel on sapphire and AlN substrate respectively. The higher sheet resistance on the sapphire substrate can be attributed to more dislocations on sapphire compared to AlN. A maximum drain current of 0.5 A/mm was obtained on the sapphire substrate and 0.93 A/mm on the AlN substrate. In pulsed conditions, the maximum current on the sapphire substrate increased to 0.6 A/mm while that on the AlN substrate increased to 0.96 A/mm. The devices on both the substrates showed a good on/off ratio in the range 10^6-10^8.

In conclusion, we have demonstrated $Al_{0.85}Ga_{0.15}N/Al_{0.7}Ga_{0.3}N$ HEMTs with record high current densities. AlN substrate leads to fewer dislocations in the channel as compared to sapphire and has better thermal conductivity as can be inferred from the pulsed I-V characteristics. Future work involves further optimizing the graded contact layer as well as improving the contact resistance to fully leverage the potential of the Al-rich AlGaN material system.

This work is partially supported by DEVCOM Army Research Laboratory and DEVCOM Army Research Office under contract/grant number SPC1000007046 | GR129057.

ED-Tue-15* - Self-Aligned p-GaN-Gate HEMTs with Regrown Contacts and an All-Refractory CMOS Compatible Metallization for Low-Voltage Power Converters

4. Electronic devices

Patrick Darmawi-Iskandar[1]
John Niroula[1], Jon Pratt[2], Cesar Roda Neve[3], Jan Strate[3], Siddharth Rajan[2], Tomás Palacios[1]
[1] Massachusetts Institute of Technology, Cambridge, MA, USA
[2] The Ohio State University, Columbus, OH, USA
[3] SOITEC Belgium N.V., Hasselt, Belgium

Abstract text: With the increasing prevalence of artificial intelligence, data centers already consume 2% of the world's electricity, a number which is predicted to double by 2026 [1]. Key to the efficiency of powering these data centers are high speed and low on-resistance power switches for which p-GaN-gate high electron mobility transistors (HEMTs) are highly promising due to their high breakdown voltage, low on-resistance, and normally-off operation. However, while >650V p-GaN-gate HEMT power switches have been heavily researched, there is little work that has explored the potential of p-GaN-gate HEMTs for critical, energy intensive low-medium voltage applications, such as the 48V-12V DC-DC power converters in data centers.

In this work we demonstrate a scaled p-GaN/$Al_{0.2}Ga_{0.8}N$/GaN (80/15/100 nm) HEMT with a p-GaN [Mg] doping of $3x10^{19}$ cm^{-3}, and a 100 nm $Al_{0.08}Ga_{0.92}N$ back barrier grown via metal organic chemical vapor deposition (MOCVD) on an 8 inch Si substrate by SOITEC. This work features several novel process modules to maximize performance as a scaled power device: 1) a self-aligned Schottky tungsten gate to maintain alignment between the gate and the p-GaN island which is increasingly difficult at scaled gate lengths 2) regrown contacts with a self-aligned source to minimize L_{GS} and contact resistance 3) a back barrier to minimize short channel effects and 4) an all-refractory CMOS compatible metallization for robust fabrication and operation with a high thermal budget. Devices with $L_G/L_{SD}/L_{GD}$ = 575/2000/1075 nm demonstrated a maximum drain current of 1.15 A/mm, an on-off current ratio exceeding 10^8, a threshold voltage of 0.97 V, on-resistances as low as 1.1 Ω·mm, and breakdown voltages exceeding 140 V which make them highly promising for use as medium-voltage power switches.

References

[1] Eren Cam et al., "Electricity 2024," International Energy Agency, January 2024. [Online].

Acknowledgements

Patrick Darmawi-Iskandar is supported in part by the National Defense Science and Engineering Graduate Fellowship (NDSEG). This work was funded in part by Samsung Electronics Co., Ltd. under Grant No. 033517-00001 (program manager Dr. Jongseob Kim) and ARO DEVCOM under Grant No. W911NF2220163 (UWBG RF Center, program manager Dr. Tom Oder).

Extended defects

2025-07-08
13:30 - 15:00
Extended defects

PC-Tue-A11 - The role of dislocations in etching porous GaN

2. Physics and characterization

Jiawei Zhang[1]
Ben Thornley[1], Piotr Sokolinski[1], Maruf Sarkar[1], Thom Harris-Lee[1], Menno Kappers[1], **Rachel Oliver**[1]
[1] University of Cambridge, UK

Abstract text: Porous GaN fabricated by electrochemical etching (ECE) is now deployed in a wide range of contexts including LEDs, sensors, and piezo-electric nanogenerators[1]. ECE is typically conducted by immersing an n-type GaN thin film into an acidic etchant solution and applying an anodic bias relative to a counter electrode. The resulting oxidation of GaN is thought to be driven by free holes, which can be formed in an n-GaN layer by Zener tunneling at high electric fields. Small pits associated with threading dislocations (TDs) have been suggested to raise the local field, initiating etching[2].

We have etched 1 μm films of n-doped GaN with dopant densities ranging from 1.8×10^{18} to 2.8×10^{19} cm^{-3}. For the most highly-doped samples, even etches of very short duration show uniform nucleation of etch pits across the surface, with no evidence of the involvement of TDs. However, for lower doping densities at lower etching voltages even samples that have been etched to completion show surfaces indistinguishable from unetched material. However, focused ion beam tomography reveals sub-surface pores branching from a central core. Back-scattered electron imaging in SEM reveals a morphology consistent with that seen in etching of distributed Bragg reflectors (DBRs) when etching occurs through nominally-undoped layers via TD pathways[1]. Since Zener tunneling requires high doping in order to create a narrow depletion region so that a reasonable probability of tunnelling arises, observation of TD-mediated etching in low doped samples at low voltages (and in undoped layers in DBRs) may suggest that acting as a field concentrating asperity is not the only role a TD plays in etching. Either increased dopant incorporation at the vicinity of the TD core, or the vulnerability of strained or dangling bonds to attack by the etchant may play a significant role.

TD-mediated etching in either DBRs or thick doped layers creates distinctive pore morphologies, and in DBRs the interplay between TD etching through undoped layers and widespread etching of the doped material, leads to complex etchant pathways between layers. Hence, it is vital to fully understand the role of TDs in order to design fabrication routes that can realise desirable microstructures for applications.

[1] PH Griffin & RA Oliver, *J Phys D Appl Phys*, 2020, **53** 383002.

[2] WJ Tseng *et al.*, *J Phys Chem C* 2014, **118** 29492

PC-Tue-A12 - Dislocation correlations in GaN epitaxial films revealed by high-resolution electron backscatter diffraction

2. Physics and characterization

Vladimir M. Kaganer[1]
Domenik Spallek[1], Philipp John[1], Oliver Brandt[1], **Jonas Lähnemann**[1]
[1] Paul-Drude-Institut für Festkörperelektronik

Abstract text: The presence and interaction of dislocations in III-nitride layers has been intensively investigated over the years as a metric of layer quality, but also in the context of strain-engineering. Averaged dislocation densities and their correlations can be derived from appropriate modeling of XRD profiles [1], while a cross-correlation analysis of high-resolution electron backscatter diffraction (HR-EBSD) patterns can provide maps of the resulting local strain distribution in III-nitride layers [2]. We use HR-EBSD-derived strain maps of two GaN epitaxial films, with threading dislocation densities r of 5×10^{8} and 1.8×10^{10} cm^{-2}, to study correlations in the dislocation arrays. From the analysis of X-ray diffraction line profiles, we expect that the dislocation strain is screened by the surrounding dislocations to reduce the elastic energy. Since the dislocation strain follows the universal law $\varepsilon\approx r^{-1}$, we find that the autocorrelation functions of the strain and rotation components measured by EBSD decay logarithmically at distances smaller than the screening distance R and become zero at larger distances, yielding R with a notably higher accuracy than from fits to XRD profiles. Distances R of 2 μm and 0.3 μm are obtained for the two samples, respectively. The experimental results are confirmed by Monte Carlo simulations of the strain and rotation maps performed by creating pairs of dislocations with opposite Burgers vectors, with the mean distance between dislocations in a pair equal to R. The pairs overlap and cannot be distinguished as separate dipoles. We find that, according to $R\,\rho^{1/2}$, the dislocation strain is screened by only 4 neighboring dislocations in both samples. In addition, we observe a strong anisotropy in the strain maps of the sample with high dislocation density, measured with a small step size of 20 nm. We show that this can be attributed to an anisotropic resolution of the EBSD measurement due to the 70° inclination of the incident electron beam, which is well reproduced in the Monte Carlo simulations by averaging over an area of 20×200 nm^2. The effect of this finite resolution is also observed in the autocorrelation functions in form of a deviation from the expected logarithmic relationship at distances below 200 nm. [1] Kaganer, Sabelfeld, Acta Cryst. A 70, 457, 2014. [2] Vilalta-Clemente, et al., Acta Mater. 125, 125, 2017.

PC-Tue-A13 - Dislocation Charge Density Quantification using Precessed STEM Differential Phase Contrast

2. Physics and characterization

Edwin Supple[1]
Kris Bertness[1], Matt Brubaker[1], Alexana Roshko[1]
[1] NIST, Boulder, CO, USA

Abstract text: GaN threading dislocations accumulate charge with density and sign varying according to their dislocation type and the dominant charge carrier. Leakage current due to these dislocations has a deleterious effect in the performance of GaN electronic devices. Previous transmission electron microscopy studies have used electron holography to determine electric potential profiles across individual dislocations and the implied charge density. The electron holography experiment, however, requires careful setup and specialized equipment to produce useful results. We demonstrate measurement of local electric field and charge density of GaN threading dislocations using precessed 4D-STEM differential phase contrast (DPC). Electric field associated with the dislocations deflects electrons as they pass through the lamella, causing a corresponding shift in the center of mass of the direct beam. Precessed scanning smooths the dynamical diffraction due to strain associated with the dislocations, improving signal:noise in the DPC signal. 4D-STEM additionally allows near-simultaneous dislocation Burgers vector identification by virtual dark field imaging. This approach can be applied broadly to other material systems such as oxides where dislocation charge is responsible for the speed of ionic diffusion.

PC-Tue-A14* - Local strain introduced by single threading dislocations in GaN studied by electron backscatter diffraction and cathodoluminescence spectroscopy

2. Physics and characterization

Domenik Spallek[1]
Vladimir Kaganer[1], Oliver Brandt[1], Thomas Auzelle[1], Jonas Lähnemann[1]
[1] Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund e.V., Berlin, Germany

Abstract text: Threading dislocations (TD) in GaN are especially relevant for the efficiency of GaN-based devices. In the present work, individual threading dislocations are investigated by high-resolution electron backscatter diffraction (HR-EBSD) and cathodoluminescence (CL) spectroscopy with high spectral resolution. These measurements are carried out on the same threading dislocation to correlate the results.

The sample under investigation is a high-purity, *C*-plane GaN layer grown by molecular beam epitaxy on a commercially available bulk GaN substrate. The TD density of this layer is estimated by panchromatic cathodoluminescence mapping to be less than 10^6 cm^{-2}. The low TD density makes it possible to measure on individual dislocations without the necessity to consider direct interactions.

Kikuchi patterns are mapped on the sample with a step size of 20 nm by EBSD. From cross correlation analysis of these patterns using the software CrossCourt, the local strain around the TD is extracted. It is shown, that the dislocations introduce a local elastic strain and rotation on the order of 3×10^{-3} and 3×10^{-3} rad, respectively for their individual tensor components. The experimental results will be compared with theoretical strain calculations around TDs.

On the same dislocations, hyperspectral cathodoluminescence (CL) maps are acquired at different temperatures with a step size of 20 nm and a spectral resolution of 0.2 nm. Apart from the reduction of the emission intensity near the dislocation induced by the piezoelectric fields of TDs with an edge component, at room temperature, the emission wavelength is shifted by approximately 0.25 nm around the dislocation. This asymmetric shift has been previously measured in [1,2], but now is correlated for the first time with a direct, localized measurement of the strain underlying the local bandgap change. Previous HR-EBSD measurements have been reported only on clustered nanopipe dislocations with a 4 times larger strain contribution [3].

References:

[1] Lähnemann *et al.*, Phys. Rev. Applied **17**, 024019 (2022).

[2] Kaganer *et al.*, Phys. Rev. Applied **12**, 054038 (2019).

[3] Ernould *et al.*, Materials Characterization **194**, 112351 (2022).

PC-Tue-A15 - The interplay in extended and point defects in BGaN epilayers grown on SiC

2. Physics and characterization

Cosmin Romanitan[1]
Juras Mickevičius[2], Nikolay Djourelov[3], Andreea-Bianca Serban[3], Oana Brincoveanu[1], Raluca Gavrila[1], Florin Comanescu[1], Arunas Kadis[2], Tadas Malinauskas[2], Emil-Mihai Pavelescu[1]
[1] National Institute for Research and Development in Microtechnologies, Erou Iancu Nicolae 126A, 077190 Voluntari, Romania
[2] Institute of Photonics and Nanotechnology, Vilnius University, Saulėtekio al. 3, LT-10257 Vilnius, Lithuania
[3] Extreme Light Infrastructure-Nuclear Physics (ELI-NP), 'Horia Hulubei' National R&D Institute for Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului Street, 077125 Măgurele, Ilfov, Romania

Abstract text: Gallium nitride (GaN) is a well-known wide-bandgap semiconductor, with remarkable electronic, optical and thermal properties, which enable efficient blue light-emitting diodes (LEDs), as well as the development of long-lifetime blue lasers. A novel class of materials based on GaN have been reported by the introduction of a third element in the lattice, to synthesize alloys with tailored physical properties. Introduction of BN in III-N compounds has recently emerged as a viable approach for lattice, band gap, refractive index, strain, and polarization engineering, which provides new opportunities for device applications. In this work, $B_xGa_{1-x}N$ epilayers with boron content, x, up to 5.6% were grown on SiC substrates by metalorganic chemical vapor deposition (MOCVD). X-ray difraction reciprocal space maps around the symmetric (0002) and asymmetric (11-24) reflections allowed evaluation the lattice constants and in-plane lattice mismatch with respect to the underlying substrate. According to our results, introduction of boron causes the decrease of BGaN lattice constants, which reduces the relative lattice mismatch with the underlying substrate, and implies the decrease of misfit dislocation density[1]. However, our results also indicate that the crystallite size of BGaN decreased significantly (by two orders of magnitude) with increasing boron content, while both the tilt and the twist of crystallites increased. Such transformation generated an increase of both screw and edge threading dislocations even despite the reduced lattice mismatch. Moreover, the interplay in the extended structural defects such as dislocations and the point defects is discussed, by correlating the X-ray diffraction with positron annihilation spectroscopy results. The microstructure degradation with increasing boron content is also reflected in the broadening of the Raman modes, as well as in the increase of yellow luminescence in PL spectra. The presented results on BGaN ternary alloys are important for the further development of boron-containing nitride materials grown on various substrates.

[1] Romanitan et al., *J. Appl. Cryst.* (2024). **57**, 1815-1822.

Ferroelectric heterostructures

2025-07-08
13:30 - 15:00
Ferroelectric heterostructures

PC-Tue-B11 - Unveiling Interfacial Dead Layer in Ferroelectric ScAlN/GaN Heterostructures

2. Physics and characterization

Ping Wang[1]
Jinlin Wang[1], Yun-Qin Li[2], Haotian Ye[1], Rui Wang[1], Qi Liu[1], Tao Wang[1], Wen-Yi Tong[2], Xin-Zheng Li[1], Chun-Gang Duan[2], Bo Shen[1], Xinqiang Wang[1]
[1] Peking University, China
[2] East China Normal University, China

Abstract text: Nitride ferroelectric semiconductors, such as ScAlN and BAlN, exhibit giant remanent polarization, ultrahigh Curie temperature, and significantly enhanced electromechanical coupling, piezoelectric, and nonlinear optical properties. These unique characteristics make them promising candidates for next-generation intelligent and multifunctional optoelectronic and electronic devices. However, the presence of interfacial dead layers with irreversible polarization remains a critical challenge, limiting their performance and integration. While dead layers in ferroelectrics have been associated with defect formation, interfacial strain, and compositional nonuniformity, direct experimental evidence for these mechanisms in nitride ferroelectrics remains absent.

In this work, we achieved high-quality, single-crystalline, fully epitaxial ferroelectric ScAlN/GaN heterostructures using plasma-assisted molecular beam epitaxy (MBE). Bipolar switchable polarization was demonstrated through detailed electrical measurements and scanning transmission electron microscopy (STEM) analyses, revealing the presence of an interfacial dead layer with unswitchable polarization near the ScAlN/GaN interface. The mechanisms underlying dead layer formation were investigated using STEM, electron energy loss spectroscopy (EELS), and theoretical calculations. Our findings indicate that nitrogen vacancies (V_N) together with compressive strain near the ScAlN/GaN interface elevate the ferroelectric switching energy barrier and degrade dielectric properties, suppressing polarization reversibility. This work provides direct insights into interfacial dead layer formation in ScAlN and highlights the critical role of defect and strain management in wurtzite ferroelectrics, paving the way for their integration into next-generation electronic devices.

PC-Tue-B12 - Nanoscale Insights Into MBE-Grown Al0.66Sc0.34N Heterostructures for Enhanced Ferroelectric Applications

2. Physics and characterization

Shaon Das[1]
Thai-Son Nguyen[2], Chandrashekar Savant[2], Debdeep Jena[3], **Baishakhi Mazumder**[1]
[1] Department of Materials Design and Innovation, University at Buffalo, Buffalo, NY 14260, USA
[2] Department of Materials Science and Engineering, Cornell University, Ithaca, NY 14853, USA
[3] Department of Materials Science and Engineering, Cornell University, Ithaca, NY 14853, USA and School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853, USA

Abstract text: Nitride-based semiconductors are widely used in high-power electronics, piezoelectric devices, and non-volatile memory. Among them, Aluminum Scandium Nitride (AlScN) has emerged as a promising ferroelectric material, with Scandium (Sc) playing a key role in switching. Incorporating Sc into Aluminum Nitride (AlN) lowers the energy barrier for polarization reversal while maintaining the wurtzite structure and shifting it to a layered hexagonal[1]. Since Sc dictates these features, understanding the nanoscale distribution of Sc is crucial, as its variations influence AlScN's structural and functional behavior[1,2]. This work examines molecular beam epitaxy (MBE)-grown AlScN-based heterostructures using atom probe tomography (APT) to investigate nanoscale elemental distribution and structure. APT provides three-dimensional chemical mapping with sub-nanometer resolution, revealing compositional fluctuations, atomic-scale clustering, and interfacial chemistry.

APT analysis of $Al_{0.66}Sc_{0.34}N$ reveals a non-uniform Sc distribution, with 2D contour plots (2DCP) showing regions where Sc concentration exceeds 46%. Frequency distribution analysis (FDA) confirms Sc clustering, while radial distribution function (RDF) analysis indicates short-range ordering, where Sc favors self-clustering. Previous study shows a hexagonal-to-cubic transition above 46% Sc[3]. Given these findings, the observed Sc-rich regions suggest phase change. These atomic-scale features may contribute to structural distortions and polarization switching behavior, as deviations from the expected phase introduce localized energy barriers affecting domain wall mobility. Additionally, APT depth profiling shows a gradual compositional transition rather than a sharp boundary in the interface, impacting strain and elemental intermixing. These nanoscale insights aid in optimizing material stability, growth processes, and interface engineering for nitride-based devices.

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PC-Tue-B13 - Unveiling the evolution of ferroelectric domains in AlScN/GaN-based heterostructures

2. Physics and characterization

Niklas Wolff[l]
Georg Schönweger[1], Ziming Ding[2], Md. Redwanul Islam[1], Christian Kübel[2], Simon Fichtner[1], Lorenz Kienle[1]
[1] Kiel University, Department of Material Science, Kiel Germany
[2] Karlsruhe Institute of Technology, Institute of Nanotechnology, Karlsruhe, Germany

Abstract text: The discovery of ferroelectric properties in wurtzite-type materials overturned the common believe that AlN and GaN-based materials do only belong to the group of pyroelectric materials. However, recent research on chemical and structural engineering demonstrated the advent of ferroelectric properties in, e.g., Sc- and B-alloyed AlN thin films.[1,2] Their high spontaneous polarization and impressive scalability below 10 nm make them ideal candidates for low-power memory devices and ferroelectric transistors based on nitride and CMOS technologies.

A fundamental understanding of the *structure-property relationships* in these ferroelectrics, i.e. the correlation of the domain nucleation and propagation within the material and the electrical behavior, will enable the optimization of its properties. In this respect, recent efforts have described possible switching pathways [3] and interface phenomena [4].

In this abstract, the role of crystal quality on the ferroelectric properties of MOCVD -grown and sputtered AlScN/GaN heterostructures is studied and interface phenomena, such as epitaxial strain are examined. Aberration corrected scanning transmission electron microscopy enabling atomic resolution investigations were performed on a JEOL NeoARM 200F microscope operated at 200 kV using the high-angle annular dark field and annular bright field detectors. The local chemical structures were studied by energy-dispersive X-ray and electron energy-loss spectroscopy.

Based on the overall crystalline coherence in these films, we reveal distinct differences in the domain morphology, nucleation and propagation. As for sputtered layers, ferroelectric switching commences with atomic reconstructions at the GaN interface, whereas nucleation at the top Pt electrode interface is observed in case of the MOCVD grown layer. Based on these findings the significance of defect engineering in wurtzite-type ferroelectrics is evident and in the focus of scientific research on future ferroelectric non-volatile memory devices and novel ferroelectric III-N heterostructures.

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PC-Tue-B14 - Ferroelectricity in AlN/GaN heterostructures

2. Physics and characterization

Georg Schönweger[1]
Niklas Wolff[1], Md Redwanul Islam[1], Isabel Streicher[2], Stefano Leone[3], Lorenz Kienle[1], Simon Fichtner[1]
[1] Kiel University, Institute for Material Science, Kiel, Germany
[2] CNR Institute for Microelectronics and Microsystems, Catania, Italy
[3] Fraunhofer Institute for Applied Solid State Physics IAF, Freiburg, Germany

Abstract text: The emergence of ferroelectricity in wurtzite materials in concert with their excellent compatibility to III-N technology promises to advance the functionality of next-generation III-N-based devices.[1] For instance, ferroelectric switching of AlScN can be exploited to achieve tunable normally-off operation as well as non-volatile memory functionality in GaN high electron mobility transistors.[2] In general, III-N-based ferroelectric memories feature inherent temperature and radiation resistance suitable for extreme environment applications. Furthermore, the recent demonstration of ferroelectricity in AlScN/GaN heterostructures grown by metal organic chemical vapor deposition (MOCVD) promises the seamless integration of ferroelectric functionality by the standard growth method of III-N devices.[3] However, the introduction of Sc into MOCVD reactors remains challenging.

In this contribution, we report on reducing the Sc content from 28 at.% down to 0 at.% in ferroelectric Al(Sc)N grown on n-type doped GaN by sputter epitaxy and MOCVD. We investigate the evolution and correlation of lattice-parameter, epitaxial strain and the ferroelectric properties such as coercive field and remanent polarization with decreasing Sc content, revealing room temperature ferroelectricity also in AlN/GaN heterostructures grown by both sputtering and MOCVD. Prior, ferroelectric switching of AlN was reported only at elevated temperatures[4] or if grown on SrTiO3 templates[5]. We relate the ability of polarization reversal to the presence of epitaxial strain by combining advanced X-Ray diffraction analysis and atomically resolved transmission electron microscopy with transient current measurements. Furthermore, we reduce the AlN film thickness from 100 nm down to 5 nm, which allows us to correlate the electrical response to the thickness dependent strain state, revealing ferroelectricity in MOCVD-grown pseudomorphic ultrathin AlN(5 nm)/GaN heterostructures. We thus demonstrate the availability of ferroelectric AlN for III-N technology.

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PC-Tue-B15 - Terahertz Optical Hall effect in AlScN/GaN and AlYN/GaN HEMT structures

2. Physics and characterization

Vallery Stanishev[1]
Isabel Streicher[2], Alexis Papamichail[3], Viktor Rindert[4], Stefano Leone[2], Vanya Darakchieva[1]
[1] Center for III-Nitride Technology, C3NiT-Janzén,Terahertz Materials Analysis Center (THeMAC), Lund University, 22100 Lund, and Linköping University, 58183 Linköping, Sweden
[2] Institute for Applied Solid State Physics IAF, 79108 Freiburg, Germany
[3] Center for III-Nitride Technology, C3NiT-Janzén, Linköping University, SE-58183 Linköping, Sweden
[4] Center for III-Nitride Technology, C3NiT-Janzén,Terahertz Materials Analysis Center (THeMAC), Lund University, 22100 Lund, Sweden

Abstract text: AlGaN/GaN high-electron-mobility transistors (HEMT) have enabled breakthroughs in high-power and high-frequency electronics. AlScN and AlYN provide a higher polarization gradient than AlGaN and hence increased sheet charge carrier density (n_s) of the two-dimensional electron gas (2DEG) if employed as barrier layers. Understanding the 2DEG properties of these HEMT structures and the factors that influence them is essential for further optimization and the development of new device designs.

Here, we report the contactless determination of 2DEG properties in AlScN/GaN and AlYN/GaN HEMT structures using the Terahertz Optical Hall Effect (OHE) [1]. These structures are grown on sapphire or 4H-SiC substrates by metalorganic vapor phase epitaxy and feature ∼10-nm thick barrier layers with Sc and Y contents ranging from 4.6% to 17.3% and 3.3% to 8.2%, respectively [2,3]. The OHE measurements were performed at magnetic field of B = 2.82 T and temperatures of 10 − 370 K. The room temperature (RT) OHE results reveal n_s of $2 - 3 \times 10^{13}$ cm^{-2} for all AlScN HEMTs and mobility parameters of $\mu = 640 - 700$ $V(s.cm)^{-1}$. For the AlYN HEMTs the mobility was found to be higher, $\mu = 730-1000$ $V(s.cm)^{-1}$, but for a slightly lower n_s in the range $1.2-2.2\times10^{13}$ cm^{-2} . These results are corroborated by eddy-current sheet resistance and contactless Hall measurements. At low temperatures the mobility parameter increases and reaches $\mu = 4000$ $V(s.cm)^{-1}$ and $\mu = 2000$ $V(s.cm)^{-1}$ for AlYN/GaN and AlScN/GaN HEMTs, respectively. The analysis indicates that at low temperatures the mobility is mostly limited by interface roughness scattering. The RT 2DEG electron effective mass parameters (m^*) was determined to be $m^* = 0.30 - 0.35m_0$, in agreement with results for AlGaN/GaN HEMTs [1, 4]. The low temperatures (10 − 130 K) OHE yielded 2DEG effective mass $m^* = 0.21-0.27m_0$, much closer to the typically accepted value of 0.23 for bulk GaN [5]. The causes for the increase of the 2DEG effective mass with temperature are discussed in detail and possible explanation, associated with polaron effects and a deviation from the classical Drude model is proposed.

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InGaN

2025-07-08
13:30 - 15:00
InGaN

GR-Tue-11 - In-Situ Synchrotron X-ray Studies of (In)GaN Growth Dynamics during OMVPE

1. Growth

Guangxu Ju[1]

[1] State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China

Abstract text: Organo-metallic vapor-phase epitaxy (OMVPE) is a leading technique for growing thin, high-quality epitaxial layers of III-V nitride semiconductors like GaN and its alloys, widely used in optical and electronic devices such as LEDs and HEMTs. Despite its broad application, OMVPE remains highly complex, involving intricate interactions among chemical reactions, thermodynamics, surface kinetics, and mass and heat transport. A major challenge lies in understanding the atomic-scale mechanisms that dictate surface morphology evolution and defect formation during growth. Building on the work of Burton, Cabrera, and Frank (BCF), epitaxial growth at the atomic level can be described through the interactions of surface steps, step kinks, and terrace adatoms. Gaining deeper insights into these mechanisms not only advances theoretical modeling but also enables precise control over surface and interface properties, crucial for optimizing device performance.

To address these challenges, we have developed a novel *in-situ*, time-resolved instrument for observing Group III nitride epitaxial film growth via OMVPE [1]. Leveraging advanced synchrotron x-ray techniques and coherent x-ray beams, our system enables *in-situ* analysis of atomic-scale island arrangements and surface steps by tracking the evolution of complex diffraction patterns [2,3].

In this talk, I will present our recent experiments on the influence of GaN off-cut direction and angle on atomic step kinetics during (In)GaN growth. In-situ surface X-ray scattering results, compared with a BCF model [4], reveal that growth kinetics are rate-limited by Ga diffusion across terraces, with faster incorporation at A steps. The findings also indicate that steps are non-transparent and step-step repulsion is asymmetric between α and β terraces. Adding hydrogen to the carrier gas helps mitigate this asymmetry. Additionally, pre-flowing TMIn without growth reveals no indium observed at either A or B step edges. However, during growth, indium is observed at the B step edge but not at the A step edge. This methodology provides a detailed understanding of GaN homoepitaxy in step flow growth mode and offers insights into achieving uniform InGaN alloy growth.

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GR-Tue-12* - Native defect diffusion in III-nitrides: understanding thermal degradation and non-radiative recombination in GaInN/GaN quantum well structures

1. Growth

Rodrigo De Vasconcellos Lourenço[1]
Heiko Bremers[2], Uwe Rossow[1], Andreas Hangleiter[1]
[1] Institute of Applied Physics, Technische Universität Braunschweig, Braunschweig, Germany
[2] Laboratory for Emerging Nanometrology, Braunschweig, Germany

Abstract text: Light emitters based on GaInN/GaN quantum well structures have revolutionized todays lighting. This revolution was achieved in part by managing the defects, such as extended defects and point defects. Only recently, the latter has gained more attention, since they could be non-radiative centers. In this context, two aspects need clarification: the identification of the defect, and the control of its density in the active region.

We investigate non-radiative recombination in GaInN/GaN single quantum wells (SQWs) with various emission wavelengths and its relation to the growth conditions of different layers within the structure.

We observe that the non-radiative lifetime in the SQW increases with increasing underlayer thickness, corresponding to a complementary error function profile of the point defect density as described by a diffusion model, regardless of whether the underlayer contains indium or not. Additionally, the non-radiative lifetime depends exponentially on the growth temperature of the buffer layer, underlayer and cladding layer. The results combined are strong evidence that point defects diffuse during III-nitride growth. A forward diffusion in the growth direction is observed, with a diffusion coefficient in the range expected for semiconductors. The activation energy represents the migration barrier of the defect, which is consistent with the nitrogen vacancy in n-type GaN. Thus, this is likely the native defect which is diffusing during growth, and acts as a non-radiative center in the QW.

Furthermore, the presence of vacancies lead to various phenomena, like group III interdiffusion at interfaces, self-diffusion, out-diffusion, impurity diffusion and void formation, which have been proposed as thermal degradation and decomposition mechanisms. Thermally activated diffusion increases the density of vacancies in the QW, enhancing non-radiative recombination. Those vacancies could then either mediate other diffusion processes or agglomerate to form voids, if present at high density.

Therefore, the processing conditions of each layer can be properly varied aiming at further reduction of vacancy diffusion into the QW. This has the potential to be beneficial to all emission wavelengths, enhancing performance and reliability of III-nitride-based light emitters.

GR-Tue-13 - Suppressing surface defects on red InGaN quantum wells by using vicinal GaN (0001) surfaces

1. Growth

Yoshinobu Matsuda[1]
Mitsuru Funato[1], Yoichi Kawakami[1]
[1] Kyoto University

Abstract text: InGaN LEDs are promising as high-efficiency, full-color light sources. However, the emission efficiency of red LEDs is significantly lower than that of blue and green LEDs. Larger In compositions for longer-wavelength emissions tend to degrade the crystalline quality of InGaN quantum wells (QWs) due to the formation of surface defects. In this study, we demonstrate a substantial reduction in surface defects, including trench defects, on red InGaN QWs by utilizing vicinal GaN (0001) surfaces.

Sapphire (0001) substrates with off-angles of 0.3° or 1.0° toward the [1-100] direction were used. The red InGaN QWs were simultaneously grown on both substrates by metal-organic vapor phase epitaxy. The epitaxial structures consist of an undoped GaN (u-GaN) underlayer (4 μm), a twenty-period $In_{0.05}Ga_{0.95}N$ (2 nm)/GaN (5 nm) superlattice, and a single InGaN (3 nm)/AlN (1 nm)/GaN (10 nm) QW.

Nomarski optical microscopy confirmed that the u-GaN underlayer on the 0.3°-off substrate exhibits a smooth surface morphology, whereas that on the 1.0°-off substrate shows a rough surface morphology due to step bunching. Surface morphology observations of the overgrown InGaN QWs by scanning electron microscopy revealed that surface defects, including small V-pits, large V-pits surrounded by anomalous growth islands, and trench defects are densely distributed across the entire area of the QW on the 0.3°-off substrate. In contrast, for the QW on the 1.0°-off substrate, the surface defect density varies depending on the surface undulation. Atomic force microscopy analyses showed that both anomalous growth islands and trench defects are significantly reduced in local regions with off-angles exceeding approximately 1°. These results suggest that preferential step-flow growth on vicinal surfaces with high step densities, which inherits the atomic ordering of the underlayers, suppresses the formation of basal stacking faults associated with the trench defects and of the anomalous growth islands. Finally, micro-photoluminescence spectral imaging at room temperature demonstrated that a part of the defect-reduced regions on the 1.0°-off substrate exhibit enhanced red emission intensities compared to the QW on the 0.3°-off substrate with high defect density. These findings provide a pathway toward the development of high-quality and highly efficient In-rich InGaN light-emitting devices.

GR-Tue-14* - Migration process of defects from high-temperature GaN buffer into InGaN/GaN quantum wells

1. Growth

Anna Toschi[1]
Yao Chen[1], Jean-François Carlin[1], Raphaël Butté[1], Nicolas Grandjean[1]
[1] Institute of Physics, École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Abstract text: The efficiency of InGaN/GaN quantum wells (QWs) in blue light-emitting diodes is significantly influenced by surface defects (SDs) originating in the high-temperature (HT) GaN buffer and forming non-radiative recombination centers (NRCs) in the QW [1]. While an InGaN underlayer (UL) prevents SDs from reaching the QW [2], the nature of these defects, their migration and incorporation processes into the QW remain barely understood.

In this study, we explore the possible migration pathways of these SDs from the HT-GaN buffer into the QW, considering two potential mechanisms: diffusion [3] and surface segregation [4]. Both mechanisms predict an exponential decay of the defect concentration in the UL as a function of the thickness, making difficult to discriminate between the two phenomena. However, diffusion should lead to an an increase of NRCs in the InGaN QW upon growth interruption (GI) before the QW growth, whereas surface segregation phenomenon does not. Photoluminescence measurements on samples with increasing GI durations reveal no degradation in QW efficiency, supporting surface segregation as the dominant migration mechanism.
Furthermore, we investigated the effect of introducing a HT-GaN layer—acting as a source of defects—either above or below the QW. When the HT-GaN layer is underneath the QW, a dramatic efficiency drop is observed. On the contrary, when the HT-GaN layer is deposited on top of the QW, there is no significant change in efficiency compared to a reference sample without this additional layer. This indicates that SDs from the HT-GaN layer do not migrate downward to the QW. If diffusion were the primary mechanism, defects from the upper HT-GaN layer would still be expected to reach the QW, contradicting the experimental results. In contrast, in case of surface segregation, defects would migrate toward the surface, reaching the QW only if the defect source is located below it. This observation supports surface segregation as the dominant migration mechanism of HT-GaN SDs into the InGaN QWs where they degrade the efficiency.

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GR-Tue-15* - MOCVD Growth of GaN/InN/GaN Quantum Wells

1. Growth

Michael Carter[1]
Md Fahel Bin Noor[1], Masahiro Kamiyama[1], Ronny Kirste[2], Seiji Mita[2], Monica Allen[3], Jeffery Allen[3], Ramon Collazo[1], Zlatko Sitar[1]
[1] Materials Science and Engineering Department, North Carolina State University, Raleigh, USA
[2] Adroit Materials, Cary, USA
[3] Air Force Research Laboratory, Eglin AFB, USA

Abstract text: InN has a direct bandgap of 0.7 eV and a reported theoretical electron mobility of >10,000 cm^2/Vs at room temperature, making it a potential candidate for applications in infrared optoelectronics and high electron mobility devices. However, it remains challenging to achieve high quality InN growth via MOCVD without plasma-assistance. We have achieved this capability through application of a growth supersaturation model to the InN growth reaction, resulting in nearly atomically flat InN layers with crystalline quality equivalent to the template (GaN/sapphire).

In this study, we extend our investigation of MOCVD InN growth to InN integration in III-Nitride heterostructures. As a model structure, we consider a GaN/InN/GaN quantum well (QW). First, an in-situ InN decomposition study is conducted, determining the maximum stable temperature for InN to be approximately 650°C. The growth of GaN on InN is thus investigated at temperatures up to 600°C. Gallium condensation on the surface is observed due to the significantly lowered activation of NH_3 in the growth reaction at low temperature. It is shown that modulation of the Gallium species flow rate can suppress metal condensation without the introduction of a flow modulation epitaxy scheme. Using optimized GaN on InN growth conditions, transmission electron microscopy (TEM) measurements show a well-defined InN QW within GaN. There is evidence of InGaN formation, corroborated by x-ray diffraction results. The InN layer is also shown to increase in roughness from bilayer surface steps (~0.5 nm) to a nearly 5 nm surface roughness. The GaN supersaturation model is utilized to compensate for the significantly lowered growth temperature while achieving similar thermodynamic conditions as in typical GaN growth (i.e. growth at 1000°C). This results in a state-of-the art InN QW with flat interfaces at both the top and bottom and a nearly 100% pure InN layer. In summary, the MOCVD growth of a GaN/InN/GaN QW has been investigated as a model for InN integration in III-Nitride heterostructures. It is shown that the system temperature must be kept below ~650°C to avoid total InN decomposition. GaN growth is optimized under these conditions via the supersaturation model to produce equivalent quality material as typical GaN growth conditions near 1000°C, as well as limit InGaN formation within the QW.

Degradation in UVC LEDs

2025-07-08
13:30 - 15:00
Degradation in UVC LEDs

OD-Tue-11 - Improved device lifetime of 275-nm-band AlGaN MQW LEDs by decelerating the degradation of carrier injection efficiency

3. Optical devices

Shigefusa CHICHIBU[1]
Kouji Okuno[2], Masaki Oya[2], Atsushi Miyazaki[2], Shinya Boyama[2], Yoshiki Saito[2], Yoshio Honda[3], Hiroshi Amano[3], Hisanori Ishiguro[4], Tetsuya Takeuchi[4], Kohei Shima[1]
[1] Inst. Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai 980-8577, Japan
[2] Toyoda Gosei Co. Ltd. Inazawa, Aichi 490-1312, Japan
[3] IMaSS & Inst. Adv. Res., Nagoya University, Nagoya, Aichi 464-8601, Japan
[4] Faculty of Science and Technology, Meijo University, Nagoya, Aichi 468-8502, Japan

Abstract text: (Synopsis)
The predicted device lifetime of 275-nm-band AlGaN-based deep-ultraviolet (DUV) light-emitting diodes (LEDs) on a (0001) Al_2O_3 substrate was greatly improved by decelerating the degradation of carrier injection efficiency (CIE) during the operation, which was accomplished by decreasing the concentration of nonradiative recombination centers (NRCs) comprising vacancy clusters in Mg-doped p-AlGaN layers.
(Contents)
An increasing demand for antivirus has accelerated the research on AlGaN-based DUV LEDs, as DUV radiation inactivates fungi, bacteria, and viruses. Although the optical output power (P_o) is increasing, the device lifetime is less than the visible LEDs. There are two degradation modes in AlGaN DUV LEDs: (I) a rapid reduction in P_o by 20-30% by the operating time (t_{op}) <100 h and (II) a gradual reduction down to 60-70% for $t_{op} \geq 100$ h. Because the *initial* degradation occurs only in DUV LEDs, several research groups have intensively investigated the mechanisms [1,2]. We have carried out aging experiments on 275-nm-band AlGaN LEDs to clarify the origins of *initial* [3] and *slow* [4] degradations, and concluded that initial P_o reduction was due to CIE deceleration caused by the depassivation of initially H-passivated preexisting NRCs in Mg-doped p-AlGaN layers. Also, vacancy clusters comprising a cation vacancy (V_{III}) and nitrogen vacancies (V_N) were ascribed to the origins of the NRCs.
This time, modified LEDs with low Mg concentration p-AlGaN layers were fabricated to decrease the NRC concentration, and the aging with forward current (I_F) of 350 mA (66 A/cm^2) and the junction temperature (T_j) of 65 °C was carried out. As a result, the *initial* degradation became nearly a half amount. By using improved MQWs, a predicted lifetime >30,000 h is obtained. Here, room-temperature photoluminescence lifetime, which represents the nonradiative lifetime, of the improved MQWs did not change until 8,000 h. The result is consistent with the model [3,4] that internal quantum efficiency of the MQWs does not change by our aging conditions.
This work was supported by MOE program for implementation of innovative infection-control and digital technologies with low CO_2 emissions, Japan.
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OD-Tue-12 - Differentiation between semiconductor- and package-related degradation of hermetically sealed far-UVC LEDs

3. Optical devices

Jan Ruschel[1]
Christoph Stölmacker[1], Neysha Lobo-Ploch[1], Jos E. Boschker[1], Natalia Kemf[1], Johannes Glaab[1], Thomas Filler[1], Tamukanashe A. Musengezi[1], Jens Rass[1], Hyun K. Cho[1], Marcel Schilling[2], Tim Wernicke[2], Steffen Knigge[1], Michael Kneissl[2], Sven Einfeldt[1]
[1] Ferdinand-Braun-Institut (FBH), Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany
[2] Institute of Solid State Physics, Technische Universität Berlin, Hardenbergstraße 36, 10623 Berlin, Germany

Abstract text: The development of UVC LEDs with short wavelengths < 235 nm (far-UVC LEDs) opens up new applications and can represent a compact alternative to gas discharge lamps, which are conventionally used in this spectral range. For example, the concentration of nitrogen oxide can be measured using far-UVC LEDs, as it has a characteristic absorption line at 226 nm. In addition, far-UVC radiation can inactivate pathogens (e.g. multi-resistant germs) while not penetrating deep into the skin. These LEDs could therefore be used for skin-friendly disinfection on humans.

Unfortunately, the use of state-of-the-art far-UVC LEDs is currently constrained by their comparatively low emission power (≈ 1 mW) and short lifetime (≤ 1000 h). The lifetime results from the operation-induced decline in emission power. It will be shown that lifetime and emission power can be significantly influenced by the heterostructure design. They often show an anti-correlation, which is typically related to processes that take place in the semiconductor layer structures.

Our studies also show that, in addition to the semiconductor layer design, a hermetic package has an influence on the reliability of far-UVC LEDs. For example, it reduces the likelihood of sudden catastrophic failures (CF), where the emission power abruptly drops to zero and the LED is usually subsequently short-circuited. However, we have also found a hermeticity-related degradation effect, resulting in a faster decrease in the emission power. Depending on the operating conditions the hermeticity can cause an additional emission power reduction of up to 60 %. At the same time, the hermeticity does not affect the electrical characteristics. Thus, it was concluded that there must be an additional degradation mechanism that takes place outside the semiconductor layers. The examination of the LED chips by energy dispersive X-ray spectroscopy (EDX) and by spectroscopic ellipsometry reveals that a carbon-containing contamination layer forms on the surface of the sapphire substrate during operation of hermetically sealed LED chips. It reduces the transmittance and thus the light extraction efficiency. Furthermore, a recovery of the emission power was observed when the hermetic package was opened, which is explained by the regression of this contamination layer.

OD-Tue-13 - Performance and Reliability of Far-UVC LEDs with DH-structure on Low-dislocation AlN Templates

3. Optical devices

Ryota Akaike[1]
Ayato Suzuki[1], Hiroki Yasunaga[1], Shuhei Ichikawa[2], Takao Nakamura[1], Masahiko Tsuchiya[3], Kazunobu Kojima[2], Hideto Miyake[1]
[1] Mie University, Tsu, Japan
[2] Osaka University, Suita, Japan
[3] Stanley Electric Co., Yokohama, Japan

Abstract text: Far-ultraviolet C (far-UVC) light has attracted much attention because it can inactivate bacteria and viruses without harming human bodies. However, far-UVC light-emitting diodes (LEDs) currently suffer from low external quantum efficiencies (EQEs) and short lifetimes. Several studies have reported improved current injection efficiencies (CIEs) in far-UVC LEDs by modifying the active layer structure [1,2]. We achieved higher EQEs in 230 nm far-UVC LEDs by employing a double-heterostructure (DH) with a thick emission layer instead of multiple quantum wells (MQWs) [3]. In this study, the performance differences between MQW-based and DH-based far-UVC LEDs were compared at different wavelengths. In addition, the dependence of DH-based far-UVC LED lifetimes on emission layer thickness was investigated.

Several MQW-based and DH-based far-UVC LEDs were fabricated on c-plane face-to-face annealed sputter-deposited AlN (FFA Sp-AlN) [4]. 20MQWs (barrier width: 3.2 nm, well width: 2.1 nm) or a thick (107 nm) emission layer with a uniform Al composition was used as the active layers of far-UVC LEDs emitting at 226 nm and 232 nm. In addition, DH-based far-UVC LEDs emitting at 230 nm with different emission layer thicknesses (39 nm to 117 nm) were prepared.

The EQEs of DH-based far-UVC LEDs were higher than those of MQW-based far-UVC LEDs for wavelengths of 226 nm and 232 nm. The EQE enhancement ratio by using double heterostructure was higher for 226 nm far-UVC LEDs (2.6 ×) than 232 nm far-UVC LEDs (1.2 ×). The EQE enhancement ratio agrees well with the CIE enhancement ratio simulated by SiLENSe for both wavelengths. L_{70} lifetime of DH-based far-UVC LEDs (λ=230 nm) was increased from 3 min to 236 min using a thicker emission layer (stress current I_{stress} was 60 A/cm^2). Relationship between $I^3_{stress}t$ and normalized EQE suggests Auger recombination is related to the lifetime at higher I_{stress}. Therefore, a reduced carrier density with a thick emission layer may be the reason for the increased L_{70} lifetime.

[1] M. Jo *et al.*, Appl. Phys. Lett. **120**, 211105 (2022). [2] H. Kobayashi *et al.*, Appl. Phys. Lett. **122**, 101103 (2023). [3] K. Uesugi *et al.*, Appl. Phys. Express **17**, 042008 (2024). [4] H. Miyake *et al.*, J. Cryst. Growth **456**, 155 (2016).

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OD-Tue-14 - Positive and negative ageing of AlGaN-based UVC LEDs: experimental analysis, interpretation and modeling

3. Optical devices

Matteo Buffolo[1]
Francesco Piva[2], Nicola Roccato[2], Carlo De Santi[2], Tim Wernicke[3], Norman Susilo[3], Daniel Hauer-Vidal[3], Luca Sulmoni[3], Michael Kneissl[4], Nicola Trivellin[5], Gaudenzio Meneghesso[2], Enrico Zanoni[2], Matteo Meneghini[1]
[1] University of Padova, Department of Information Engineering & Department of Physics and Astronomy, 35131 Padua, Italy
[2] University of Padova, Department of Information Engineering, 35131 Padua, Italy
[3] Technische Universität Berlin, Institute of Solid State Physics, 10365 Berlin, Germany
[4] Technische Universität Berlin, Institute of Solid State Physics & Ferdinand-Braun-Institut (FBH), Berlin, Germany
[5] University of Padova, Department of Information Engineering & Department of Industrial Engineering, 35131 Padua, Italy

Abstract text: Over the last years, UVC LEDs have enabled cost-effective and efficient disinfection systems and tools [1], [2]. In this work we investigate the optical degradation kinetics of 265 nm SQW LEDs [3], focusing in particular on the non-monotonic and current-dependent optical power variation, with the aim of identifying the root causes of the optical instability of solid-state UVC emitters.

By leveraging a series of accelerated lifetime tests (ALTs), coupled with conventional opto-electrical characterizations and deep-level optical spectroscopy (DLOS) analyses, we found that i) during ageing, the emitted ouput power varies non-monotonically and current dependently, showing an increase (positive ageing), during the first stage of stress. We also found that ii) the positive ageing process is non-recoverable, and that iii) the subsequent decay (negative ageing) is correlated with the increase in concentration of a deep level located at E_c – 2.5 eV.

To pinpoint the physical origin of the positive ageing process, we coupled the experimentally obtained defect properties with a numerical simulation framework built on Sentaurus Synopsys, calibrated on similar devices to reproduce with high accuracy their current-voltage characteristics [4]. Based on this, we first demonstrated that the positive ageing is associated with the formation of negative fixed charge at the interface between the last barrier (LB) and the undoped interlayer (IL): this process improves holes injection, ultimately promoting radiative emission within the active region. Then, we reproduced the overall optical power trends, both at low and high measuring bias levels, by considering the cumulative effect of nonradiative recombination centers originating within the QW, which decrease the optical power, and of the aforementioned negatively charged centers at the IL/LB interface, which act in the opposite direction.

The degradation model proposed within this work was found to well describe the experimental behavior of the UV-LEDs, thus contributing to increase the current understanding of the lifetime-limiting mechanisms affecting state-of-the-art AlGaN-based UVC LEDs.

[1] 10.3390/ELECTRONICS10141703; [2] 10.1038/s41598-021-94070-2; [3] 10.1063/1.5010265/35677; [4] 10.1063/5.0144721/2884739

Fundings: PRIN 20225YYLEP, EU; 03COV10D, BMBF; ULTRA.sens project, BMWK; K415/2021, Leibniz Society

OD-Tue-15 - Degradation of far-ultraviolet light emitting diodes on AlN substrate

3. Optical devices

Shashwat Rathkanthiwar[1]
Maki Kushimoto[2], Yudai Shimizu[3], Kazutada Ikenaga[3], Mayank Bulsara[3], Keitaro Ikejiri[3], Hiroshi Amano[4], **Leo J. Schowalter**[1]
[1] Lit Thinking, Orlando, Florida 32826, USA
[2] Graduate School of Engineering, Nagoya University, Aichi 464-8603, Japan
[3] Taiyo Nippon Sanso, Innovation Unit, Yokohama, Kanagawa 220-8561, Japan
[4] Center for Integrated Research of Future Electronics, Institute of Materials Research and System for Sustainability, Nagoya University, Nagoya, 464-8601, Japan

Abstract text: The safety and efficacy of far-UVC radiation (<240 nm) for indoor pathogen inactivation has spurred research on far-UVC light sources. While nitride LED technology promises to replicate the advantages of visible and near-UV LEDs like compact size, low operating power, and tunable wavelength, a major challenge is the sharp decrease in efficiency and lifetime (at practical current densities) at shorter wavelengths (high Al content). Perhaps this degradation is linked to the increased point defect incorporation during high Al-content AlGaN growth or to a greater susceptibility of point defects (or point defect complexes) to be activated by high current at high Al composition. The precise mechanism is unknown, and, in this study, we are investigating the impact of multi-quantum well (MQW), electron blocking layer (EBL), and graded-AlGaN hole injection layer (HIL) variations on 240-nm LED lifetimes. The LEDs were grown on AlN substrates using a low-pressure, resistive-heated, horizontal-flow metalorganic chemical vapor deposition (MOCVD) which achieved step-flow morphology and pseudomorphic growth. Cross-sectional transmission electron microscopy corroborated the high-quality epitaxial growth. The Si-doped $Al_{0.79}Ga_{0.21}N$ n-contact layer exhibited a sheet resistance of 405 Ω/□. TLM contacts on the p+ GaN contact layer showed a linear I-V behavior confirming an Ohmic contact formation. LEDs exhibited a sharp electroluminescence with FWHM of ~11 nm. Accelerated constant-current degradation tests [1] were conducted in the range of 0.7 to 4 kA/cm^2 (corresponding to a forward voltage ranging from 7.9 to 11.3 V, respectively, at the start of the test). A 12-fold reduction (from 520 to 42 seconds) in L50 lifetime (50% drop from the initial output power) was observed for the 6-fold increase in current density. Notably, increasing the HIL start composition from 90% to 95% Al led to 2.5 and 5 times decrease in the L50 lifetime at 0.7 and 4 kA/cm^2, respectively, which supports the hypotheses that point defects at higher Al content are susceptible to higher degradation rates for far-UVC LEDs.

[1] Zhang et al., physica status solidi (a), **221** (2024) 2300946.

Power Electronics 2 (Reliability)

2025-07-08
15:30 - 17:00
Power Electronics 2 (Reliability)

ED-Tue-16 - Elevating Reliability Standards: Advanced Methodologies for HV GaN Power Devices and Systems

4. Electronic devices

Gabriel Lansbergen[1]
[1] Infineon Technologies Austria AG, Siemensstraße 2, 9500 Villach, Austria

Abstract text: Historically, the silicon-derived JEDEC product qualification has served as a baseline for GaN power device qualification in the industry. Nevertheless, it has been widely acknowledged that JEDEC standards may not always be sufficient to guarantee reliable operation over the device's lifetime. To address this challenge, Infineon has been actively working to elevate the quality and reliability of GaN devices to match the standards of silicon-based devices, and has taken an active role in the JEDEC JC-70 WBG committee to drive new standards for GaN power devices. In this work, we will describe our general approach to high-voltage GaN power device reliability. Specifically, we will explain how Infineon's GaN qualification is based on condition-specific stresses and does guarantee the required lifetime and quality.

The proof of fitness for use in industrial applications ultimately relies on lifetime models extracted for both intrinsic and extrinsic branches. First, we will discuss the methodologies for intrinsic lifetime extraction using two examples: off-state stress and hard switching stress. The former is a more straightforward approach, whereas the latter employs a sophisticated stressor model based on switching locus variation.

Secondly, to assess off-state extrinsic failure rates we have conducted large-scale Early Life Failure Rate (ELFR) studies on several hundred thousand parts. This has enabled us to extract a specific extrinsic reliability model and determine an extrinsic failure rate below 1 FIT (failure in time) for typical use conditions and a 15-year lifetime. Furthermore, this work shows how ELFR studies can be also beneficial during technology development to investigate the root cause of this extrinsic behavior. By designing specific ELFR studies with devices with different geometries, it is possible to identify the key elements responsible for such early failures and eliminate them before entering in the mass production phase.

Thus, by developing and refining advanced methodologies for GaN power devices, we can create robust and reliable parts that are suitable for widespread adoption in high-end industrial applications

ED-Tue-17* - 2.7kV Enhancement-Mode GaN-on-Si Multichannel Tri-gate junction HEMT using SiO2/p-doped NiO as gate oxide

4. Electronic devices

Amirhossein Esteghamat[1]
Zheng Hao[1], Mohammad Rezaei[1], Kai Cheng[2], Walid El Huni[3], Huseyin Cakmak[3], Gilberto Curatola Curatola[3], Samir Mouhoubi[3], Elison Matioli[1]
[1] École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
[2] Enkris Semiconductor Inc., Suzhou, China
[3] Huawei Nuremberg Research Center, Nuremberg, Germany

Abstract text: Multi-channel GaN high electron mobility transistors (HEMTs) utilizing a stacked two-dimensional electron gas (2DEG) channels show superior on-state performance in comparison to conventional single channel HEMTs due to increased carrier concentration while maintaining high mobility within each channel. However, achieving enhancement-mode (E-mode) operation in such structures remains challenging due to this high carrier concentration. Tri-gate structure utilizing the gate Schottky contacts was shown to reach E-mode behavior, however the full depletion of electrons required highly scaled fins, down to 15 nm.

This work presents an E-mode multi-channel tri-gate junction HEMT using a novel gate dielectric stack composed of 2.5 nm SiO_2 and 120 nm p-doped NiO. The SiO_2 layer acts as a protective barrier during NiO sputtering, while the p-doped NiO introduces a large built-in potential at its interface with GaN, depleting electrons in the 2DEG and enabling positive threshold voltage (V_{th} = 0.7 V at 1 μA/mm) for fin-widths of 40 nm – nearly 3-times larger than previous works. Electrical characterization reveals a high breakdown voltage of 2.7 kV at 1 μA/mm and a low on-resistance of 2.8 mΩ·cm^2. The gate dielectric stack combined with tri-gate structure results in a superior gate control, reduced leakage current, and enhanced V_{th} stability. The double sweep characteristic of the device shows an on/off ratio of 10^9, a subthreshold slope (SS) of 60–63 mV/dec, and a threshold voltage shift (ΔV_{th}) of less than 0.05 V. Unlike conventional undoped oxides, NiO induces a charge depletion region, preventing excess electron accumulation and eliminating interface charge trapping. This results in a stable threshold voltage (V_{th}) with minimal hysteresis, enhancing device reliability. Additionally, the favorable band alignment of NiO suppresses electron spillover into the oxide, further reducing trapping effects. The small SS parameter, which is near to the theoretical limit, is related to the effective gate control over the channel in the tri-gate structure.

The proposed approach enables E-mode operation with larger fins, which results in low on-resistance together with high breakdown voltage. This result outperforms conventional GaN HEMTs and surpasses the 4H-SiC limit, significantly advancing the potential of GaN HEMTs for high-power applications.

ED-Tue-18 - Monolithic Optical Cascode GaN HEMT for High Voltage Switching Applications

4. Electronic devices
Jung-Han Hsia[1]
Zhongyunshen Zhu[1], Patrick Darmawi-Iskandar[1], **John Niroula**[1], Cesar Roda Neve[2], Jan Strate[2], Tomás Palacios[1]
[1] Massachusetts Institute of Technology
[2] SOITEC Belgium N.V

Abstract text: In recent years, the rapid growth of artificial intelligence has increased the need for more efficient and reliable grid electronics, where medium-high voltage (5–50 kV) power systems play a key role. To achieve the required blocking voltage, these systems often stack multiple power devices. However, this stacking approach not only demands advanced driving circuitry but also brings about reliability challenges due to electromagnetic interference (EMI) [1]. Although there is significant interest in optically controlled power devices, most developments have focused on photoconductive switches, which are mainly suited for pulsed-power applications due to the lack of efficient continuous ultraviolet light sources. Infrared optical switches have also been implemented to mitigate EMI issues in a cascode configuration [2]; however, such integration can add complexity and introduce parasitic inductances to the switching circuit.

In this work, we propose a monolithic optical cascode based on a p-GaN epitaxial structure. The device comprises an optically controlled, enhancement-mode (E-mode) p-GaN HEMT, which is monolithically cascaded with a depletion-mode (D-mode) high-voltage HEMT. This design decouples the optical control from the voltage-blocking capability of a lateral HEMT, enabling the scaling of the L_{GD} in the low-voltage optical switch to enhance the device's optical gain while preserving the voltage-blocking capability of the D-mode device. Upon illumination, carriers are generated in the depletion region in the E-mode device, turning on the cascode. **In the p-GaN optical switch, we utilized an ohmic gate for efficient hole removal and demonstrated a sub-ms turn-off time with an optical gain exceeding 10^4 A/W.** By leveraging the cascode structure, the breakdown voltage is enhanced without compromising the optical gain. **Initial experimental results have successfully demonstrated a monolithic cascode capable of switching up to 150 V without persistent photoconductivity.** Future work will involve simulations to further understand the carrier dynamics and experimental design optimization,

References

[1] S. K. Mazumder et al., *IEEE Trans. on Power Electronics*, **31**, 6562-6574 (2016).

[2] A. Mojab, et al*., IEEE Transactions on Electron Devices*, **64**, **3**, 796-804 (2017)

This work is supported in part by U.S. Office of Naval Research under Grant N00014-22-1-2468.

ED-Tue-19* - Study on Threshold Voltage Control of Power GaN-MIS Devices Using Floating Gate Structure

4. Electronic devices

Xigen LI[1]
Manato DEKI[2], Hirotaka WATANABE[3], Shun LU[1], Jia WANG[4], Shugo NITTA[5], Yoshio HONDA[6], Hiroshi AMANO[6]
[1] Department of Electronics, Nagoya University, Nagoya, Japan
[2] Deep Tech Serial Innovation Center, Nagoya University, Nagoya, Japan
[3] Institute of Materials and System for Sustainability, Nagoya University,Nagoya, Japan
[4] Institute for Advanced Research, Nagoya University, Nagoya, Japan
[5] Innovation center for semiconductor and digital future, Mie University, Mie, Japan
[6] Institute of Materials and System for Sustainability, Nagoya University, Nagoya, Japan

Abstract text: Background:

Achieving a high-performance GaN power FETs with MIS structure requires balancing normally-off operation with high electron mobility. In inversion channel MISFETs, increasing channel Mg doping raises the threshold voltage (V_{TH}) but degrades channel electron mobility due to impurity scattering [1]. Power GaN-MISFET, as the next generation power devices, have become particularly important to reduce channel resistance while maintaining reliable operation. Therefore, we propose applying the floating gate (FG) structure to GaN power MISFETs. By controlling V_{TH} through electron injection into the FG structure, positive V_{TH} shift while maintaining channel mobility is simultaneously realized.

In traditional silicon memory MOSFET, as many P/E cycles as possible have been studied. But in this work, we studied the extension of charge retention after a one-time electron injection without increasing interface states.

Experiments:

FG capacitors were fabricated on a lightly doped n-GaN wafer. The FG structure (SiO_2/SiN/SiO_2 stack), formed by PECVD SiO_2 and SiN deposited by sputtering, followed by Ni/Au anode and Al cathode deposition via RH. After that, we injected electrons using voltage pulses and measured the capacitance-voltage characteristic.

Results:

First, we evaluated the density of SiO_2/GaN interface states before and after electron injections through the Terman method. The results indicate that pulse amplitude of 8 MV/cm (The electric field strength applied to the tunnel-SiO_2 during pulsing) or lower do not lead to an increase in interface states. This result indirectly demonstrates that, in MISFETs applications, an appropriate pulse intensity does not degrade the interface quality of MISFETs channel, which allows channel mobility to be well maintained.

Additionally, by measuring the V_{FB} time dependence under different pulse amplitudes, we found

that, while a higher pulse amplitude results in a larger V_{FB} shift even up to 11V, the time dependence V_{FB} significantly reduces. This is because a stronger pulse causes severe damage to the tunnel-SiO_2 layer, accelerating charge loss, which is assisted by trap-assisted mechanisms. And when the pulse intensity is below 6 MV/cm, the samples exhibit a good charge retention, with the charge loss predicted to be only 26.2% after ten years.

[1] R. Tanaka, et al., Applied Physics Express, 12, 054001, (2019)

ED-Tue-20 - Rhenium-Based Refractory Schottky-Gated AlGaN/GaN HEMTs with Record Ion/Ioff at 500C

4. Electronic devices

John Niroula[1]
Qinxyun Xie[1], Jon Pratt[2], Patrick Darmawi-Iskandar[1], Siddharth Rajan[2], Tomás Palacios[1]
[1] Massachusetts Institute of Technology, Cambridge, MA, USA
[2] The Ohio State University, Columbus, Ohio, USA

Abstract text: High temperature (HT) electronics has received much interest recently due to many critical emerging applications in geothermal energy, hypersonic flight, deep oil drilling, and space exploration. Due to their low intrinsic carrier concentration, wide-bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) are fundamentally better suited for HT operation, especially beyond the typical 250°C temperature limit of standard silicon and silicon-on-insulator (SOI) technology. GaN in particular is especially promising due to its superior transport properties over SiC and its widespread availability in the lighting, power, and RF domains; however, at HT, GaN HEMTs typically suffer from significant gate leakage and gate metal diffusion, both of which significantly reduce device performance and reliability.

To reduce these two effects, this work demonstrates a high performance, all refractory AlGaN/GaN HEMT with a rhenium-based schottky T-gate metallization and a tungsten ohmic metallization. The fabricated device has an $I_{on}/I_{off} = 1.3\times10^5$ at 500°C, which, to the best of the authors' knowledge, is the highest on/off ratio at 500°C of any AlGaN/GaN or SiC device reported in the literature. Furthermore, the maximum on-current of 0.9 A/mm is also amongst the highest reported at 500°C. This is possible due to several key contributions which include 1) a refractory rhenium-based gate metallization with a high schottky barrier height due to rhenium's high work function; 2) regrown n^{++} GaN contacts with a novel self-aligned sputtered tungsten liftoff process using SiO_2 for the ohmic metallization; 3) a HT stable ALD AlON dielectric layer that serves as both an etch stop for the gate formation as well as a HT passivation layer. Additionally, the device is analyzed for multiple high temperature measurement cycles to understand the stability of the structure and metallization. Thus, this work progresses AlGaN/GaN HEMTs HT performance towards realization of truly thermally-hardened, robust HT RF devices.

Acknowledgements
Device fabrication was conducted at MIT.nano. This work was sponsored in part by the Air Force Office of Scientific Research (AFOSR) under award no. FA9550-22-1-0367, by Lockheed Martin Corporation under award no. 025570-00036, and by ARO DEVCOM under Grant No. W911NF2220163 (UWBG RF Center, program manager Dr. Tom Oder).

LEDs and advanced spectroscopy

2025-07-08
15:30 - 17:00
LEDs and advanced spectroscopy

PC-Tue-A16 - Using both faces of bulk GaN substrates for functional devices

2. Physics and characterization

Henryk Turski[1]
Len van Deurzen[2], Eungkyun Kim[2], Naomi Pieczulewski[2], Zexuan Zhang[2], Anna Feduniewicz-Zmuda[3], Mikolaj Chlipala[3], Marcin Siekacz[3], David Muller[2], Huili Grace Xing[2], Debdeep Jena[2]
[1] Institute of High Pressure Physics PAS, Warsaw, Poland, and Cornell University, Ithaca, NY, USA
[2] Cornell University, Ithaca, NY, USA
[3] Institute of High Pressure Physics PAS, Warsaw, Poland

Abstract text: An important material property of III-nitrides utilized in heterostructure design is the built-in polarization. Since GaN primarily crystallizes in the wurtzite structure, which breaks inversion symmetry along the c-axis [0001], opposite surfaces along this direction exhibit drastically different physical and electronic properties. This characteristic can be leveraged for specific applications. However, since polarization is dictated by the substrate polarity, the use of a single wafer has traditionally implied only one alignment of polarization in the devices grown on top of it.

In this work, we propose leveraging the unique advantages of the GaN material system, its wide range of possible applications, and access to high-quality bulk substrates [1] to develop a new method for the monolithic integration of electronic and optoelectronic devices on the same wafer. By utilizing consecutive epitaxial growth processes on both polarities of GaN substrates, i.e., the gallium face (0001) and nitrogen face (000-1), it is possible to achieve structures with distinct physical and chemical properties on the same bulk crystal.

We demonstrate the monolithic integration of a metal-polar light-emitting diode (LED) and a nitrogen-polar high electron mobility transistor (HEMT) [2]. We show pulse operation of the LED controlled via biasing the HEMT. Additionally, an alternative device using a similar concept is presented, namely the use of both polarities for a double-sided LED. Due to higher indium incorporation for nitrogen-face growth, yellow-amber emission was obtained for that growth, while blue emission was achieved for Ga-polar growth.

The obtained integrated structures can pave the way for new applications and completely new device functionalities.

[1] K. Grabianska, P. Jaroszynski, et al., *Electronics*, **9** (2020).

[2] L. van Deurzen, E. Kim, et al., *Nature*, **634** (2024) 334.

PC-Tue-A17 - Cavity Plasmon: Enhanced Luminescence Effect on InGaN Light Emitting Diodes

2. Physics and characterization

Peng CHEN[1]
Yuyin Li[1], Hong Zhao[1], Zili Xie[1], Yi Shi[1], Rong Zhang[1], Youdou Zheng[1]
[1] School of Electronic Science and Engineering, Nanjing University, Jiangsu, Nanjing, 210093, China

Abstract text: We fabricated polygonal nanoholes in the top p-GaN layer of the InGaN/GaN light-emitting diode, followed by the deposition of Au/Al metal thin film within the nanoholes to create metal microcavities, thereby constructing the surface plasmon structure. The findings indicate that with increased current injection, the light output of the LEDs rose by 46%, accompanied by a shift of the gain peak position towards the plasmon resonance energy. The maximum enhancement factor increases to 2.38 as the coupling distance decreases from 60 nm to 30 nm. Interestingly, time-resolved photoluminescence data showed that the spontaneous emission decay time lengthened due to the plasmon coupling, suggesting the presence of a new plasmon coupling mechanism. Finite-Difference Time-Domain simulation results show that the electric field is localized at certain locations around the metal microcavity, generating a new type of shape-sensitive plasmon, named **Cavity Plasmon** here. This intense localization leads to a longer lifetime and enhances the recombination efficiency of excitons. We discuss several unique properties of the cavity plasmon generated by the polygonal metal microcavity with several specific angular shapes. The results demonstrate that the cavity plasmon generated by the polygonal metal microcavity is a highly promising technique for enhancing the light emission performance of of relevant semiconductor optoelectronic devices.

PC-Tue-A18 - Impact of p-n junction built-in and polarization field on carrier injection into InGaN/GaN quantum wells: a nano-cathodoluminescence investigation

2. Physics and characterization

Jürgen Christen[1]
Gordon Schmidt[1], Frank Bertram[1], Peter Veit[1], Christoph Berger[1], Armin Dadgar[1], Benjamin Utsch[2], Friedhard Römer[2], Bernd Witzigmann[2], André Strittmatter[1]
[1] Otto-von-Guericke-University Magdeburg, Germany
[2] Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

Abstract text: The impact of the built-in field on the transport properties of charge carriers and/or excitons is directly investigated comparing identically grown InGaN/GaN quantum well (QW) structures with and without a p-n junction. In cathodoluminescence (CL), the primary electron beam generates excess electron hole pairs partially forming excitons according to the Saha equation (dilute e-h plasma). The built-in field of the p-n junction separates the generated excess carriers in the space charge region reducing their radiative recombination. In contrast, the neutral exciton is not affected by the electric field while its dipole character gives direct access to the field gradient. However, the simplistic assumption of perturbation theory is no longer appropriate as the electric fields involved may exceed the critical field strength for exciton dissociation. We will discuss our results in the Blossey model [1].

A direct nanometer-scale correlation of the structural and optical properties by means of CL directly performed in scanning transmission electron microscope (STEM-CL) at low temperatures (T = 17 K) of InGaN QWs is presented on identically grown wells embedded into a p-n junction and undoped GaN layers. The QWs are sandwiched between a p-n junction formed by Si-doped GaN with [Si] = $7x10^{18}cm^{-3}$ nominal Si-concentration and Mg-doped GaN with [Mg] = $2x10^{19}$ cm^{-3}. For comparison, nominally identical QWs were placed in an undoped structure.

STEM-CL linescans taken along the growth direction reveal striking differences for the QW emission within p-n junctions as compared to the undoped sample: below the first QW in the n-GaN layer, the emission peak is at 437 nm and jumps abruptly to longer wavelengths at (λ_{peak} = 445 nm). For the InGaN MQW embedded in undoped GaN, the spectral change of the QW emission is completely contrary. Here, the QW peak jumps to shorter wavelength (from λ_{peak} 445 nm to 439.8 nm). Despite the usual assumption of different In concentration in the first quantum film, this is contradictory to the opposing spectral shift. Furthermore, a clearly different carrier/exciton capture results: while in the p-n diodes the capture is limited to the vicinity of the space-charge region, the nominally undoped structure shows a distinct long-range transfer.

[1] D. F. Blossey, Phys. Rev. B 2, 3976 (1970).

PC-Tue-A19 - Potential of AlN films deposited on annealed AlN/Al2O3 templates for high-temperature devices

2. Physics and characterization

Jaime Freitas[1]
James Culbertson[2], Nadeemullha Mahadik[2], James Lundh[2], Ryota Akaike[3], **Hideto Miyake**[3]
[1] Naval Research Laboratory, Washington DC 20375 USA
[2] Naval Research Laboratory
[3] Graduate School of Engineering, Mie University

Abstract text: There is an emerging need for electronics able to operate in harsh thermal environments (500°C to >800°C) that outperform current commercially available high-performance devices. The ultra-wide-band-gap (UWBG) material system AlN/AlGaN has been proposed as a platform for devices in extreme thermal environments. UWBG materials exhibit lower intrinsic carrier concentrations than WBG materials, which results in substantially reduced leakage currents at elevated temperatures. AlN films of 450 nm of thickness were deposited on 2-inch c-plane sapphire substrates, with -0.2° misorientation toward [100] direction, by RF sputtering. These templates were annealed at ~1700 °C using a "face-to-face method"[1] to minimize AlN decomposition and avoid contamination from the environment. The face-to-face annealed (FFA) AlN templates were used as substrates for subsequent AlN MOVPE[1] depositions of 200, 550, and 1550 nm.

HR-XRD shows that the FFA Sp-AlN layer deposited on the sapphire substrate has a very sharp interface and appears to be almost fully relaxed; the crystalline quality of this AlN film is very high as indicated by a full width at half maximum (FWHM) of 39.6 arcsecs; the FWHM of homoepitaxial films continues to improve with thickness. Raman scattering measurements show the FWHM of all allowed phonon lines decrease asymptotically with increasing homoepitaxial film thicknesses, while the line-intensities increase linearly, and the Raman-shifts decrease asymptotically. The 4K CL spectra of the FFA template and the three epitaxial films clearly show the incorporation of impurity related point defects[2] reduce drastically with increasing film thicknesses. SIMS depth profile is scheduled to identify the chemical nature of the impurities. The 4K CL spectra of the 1550 nm epitaxial film clearly show an emission band associated with the annihilation of excitons[3]. Preliminary 4-point probe resistivity measurements show the sample is highly resistive (³GW/ð); more detailed data will be presented. These results clearly verify the high crystalline quality of the homoepitaxial films and their potential use for high-temperature development.

(1) K. Uesugi et al., Appl. Phys. Express 12 (2019) 065501 (2019) ; (2) T. Nagashima et al., Appl. Phys. Express 5 (2012) 125501; (3) E. Silveira et al., J. Crystal Growth 281 (2005) 188.
Work supported by the Office of Naval Research

PC-Tue-A20 - Defects in Submicron-Sized Platelets For Use as Micro-Light-Emitting-Diodes Studied by Hyperspectral Cathodoluminescence Imaging

2. Physics and characterization

Anders Gustafsson[1]
Hira Usman[2], Zhaoxia Bi[3], Lars Samuelson[4]
[1] Institute of Nanoscience and Applications, Southern University of Science and Technology, Shenzhen, 518055, China and Solid State Physics and NanoLund, Lund University, Box 118, Lund SE-221 00, Sweden
[2] Institute of Nanoscience and Applications, Southern University of Science and Technology, Shenzhen, 518055, China
[3] Hexagem AB, Ole Römers väg 1H, SE-22363 Lund, Sweden and Future Display Institute of Xiamen, Xiamen 361005, China
[4] Institute of Nanoscience and Applications, Southern University of Science and Technology, Shenzhen, 518055, China; Solid State Physics and NanoLund, Lund University, Box 118, Lund SE-221 00, Sweden

Abstract text: The next generation of displays will use micron-sized light emitting diodes (micro-LEDs) emitting red, green and blue colours as individual pixels. The holy grail for micro-LEDs is to cover all three colours with III-nitrides. The main challenge is the red-emitting InGaN LEDs. The large lattice mismatch between the InGaN quantum wells (QWs) and the GaN buffer layer causes strain and defects, which significantly reduce the efficiency of micro-LEDs. We have investigated the optical properties of red micro-LED structures based on submicron-sized InGaN platelets.

The platelets are grown by selective area growth from a regular array of submicron-sized holes in a mask on GaN/sapphire substrates by metal-organic chemical vapour deposition in a three-step process: I) Growth of InGaN pyramids; II) Chemical mechanical polishing to make a template with a flat top surface; III) Growth of a stack of layers comprising: 1) A lower barrier matching the template in composition; 2) A single QW with higher indium content; 3) A top barrier matching the template in composition. Optionally, a transition layer with a slightly higher indium content than in the barrier is grown below the QW to promote indium incorporation into the QW.

The optical properties were studied by hyperspectral cathodoluminescence (CL) imaging at room temperature. The QW emission dominates the spectrum, with contributions from the other layers: The GaN substrate; the barriers; and the transition layer. The identification of the emission peaks was done by the ratio of peak intensities and apparent shape of the emitting area at different acceleration voltages, different penetration depths.

When imaging the QW emission in top view, we observe dark lines in a significant portion of the platelets. As the different layers emit at different wavelengths, these dark lines can also be observed when imaging the barrier emission. Most of the dark lines appear in the different layers, with some minor shifts in position. A combined transmission electron microscopy and CL study of the same platelets identified the dark lines in the CL images as stacking mismatch boundaries (SMBs), where an ABAB stacking meets an ACAC in the c-plane. Since SMBs reduce the efficiency of light emission, it is essential to identify the origin of the defects and to eliminate the source. The latter will be demonstrated in the presentation.

Novel devices

2025-07-08
15:30 - 17:00
Novel devices

OD-Tue-16B - Far-Ultraviolet Second Harmonic Generation from AlGaN-based Waveguides

3. Optical devices

Ryuji Katayama[1]
Masahiro Uemukai[1], Tomoyuki Tanikawa[1]
[1] Graduate School of Engineering, The University of Osaka, Suita, Osaka Japan

Abstract text: The invention of InGaN blue light-emitting devices completed the set of high-brightness, energy-efficient, compact, and long-lifetime LEDs for the primary colors, enriching our lives and enabling new applications. However, far ultraviolet (FUV) wavelengths remain inaccessible to semiconductor light emitters. A high sterilization efficacy of FUV light, especially below 230 nm, allows for human skin surface irradiation without deep tissue damage, offering a novel infection prevention method beyond vaccines and masks. FUV lasers also serve in semiconductor manufacturing for inspection and processing. Yet, excimer lamps and AlGaN LEDs suffer from low efficiency and short lifetimes, necessitating new FUV light sources.

Our lab aims to generate FUV light by halving the wavelength of a high-efficiency, long-lifetime blue laser using a wavelength conversion device. We chose AlGaN semiconductors for the wavelength conversion crystal due to their strong optical nonlinearity comparable to ferroelectrics, surpassing $CsLiB_6O_{10}$ and β-BaB_2O_4, with chemical stability and high optical damage resistance for high power. Despite this, efficient wavelength conversion in non-ferroelectric, optically isotropic semiconductors was deemed impossible, leaving AlGaN's nonlinearity unexplored. But we fabricated novel (Al,Ga)N-based optical waveguide devices with inverted crystal orientations (*i.e.* polarity inversion) via epitaxial growth combined with oxidation [1,2], or wafer bonding [3], and successfully demonstrated wavelength conversion [4]. We also proposed a novel "Transverse Quasi-Phase Matching (TQPM)" device structure for high-efficiency conversion by strongly interacting artificially modulated nonlinear polarization, achieved by introducing polarity inversion along the stacking direction, with high-order transverse mode electromagnetic waves of the harmonic [5].

This presentation will cover the world's first 229 nm FUV second-harmonic generation from a semiconductor device [6], efficiency enhancements via multiple polarity inversions [7] and internal field enhancement using strained-layer superlattices [8], and the demonstration of an all-nitride FUV light source pumped by a custom-made InGaN DFB laser [9].

[1] K. Ikeda and R. Katayama *et al*., phys. stat. sol. (b) 2400161 (2024).

[2] K. Shojiki *et al.*, J. of Cryst. Growth **574**, 126309 (2021).

[3] N. Yokoyama and R. Katayama *et al.*, Jpn. J. of Appl. Phys. **61**, 050902 (2022).

[4] H. Ishihara and R. Katayama *et al.*, Jpn. J. of Appl. Phys. **61** SK1020 (2022).

[5] N. Yokoyama and R. Katayama *et al.*, Appl. Phys. Express **15**, 112002 (2022).

[6] H. Honda and R. Katayama *et al.*, Appl. Phys. Express **16**, 062006 (2023).

[7] T. Tamano and R. Katayama *et al.*, Appl. Phys. Lett. **126**, 032108 (2025)

[8] S. Malik and R. Katayama *et al.*, ACS Crystal Growth & Design, accepted.

[9] T. Fukamachi and R. Katayama *et al.*, Appl. Phys. Express **17**, 052004 (2024).

OD-Tue-17B* - Enhancement of the non-linear optical coefficient in the strained-layer superlattice structure via piezoelectric polarization in far-UV SHG.

3. Optical devices

Shahzeb Malik[1]
HIroto Honda[1], Kanako Shojiki[2], Hideto Miyake[3], Masahiro Uemukai[1], Tomoyuki Tanikawa[1], Ryuji Katayama[1]
[1] The University of Osaka, Japan
[2] Kyoto University, Japan
[3] Mie University, Japan

Abstract text: Inactivation of viruses, disinfection of germs, sterilization of the human body, sensing, and many more diversified global applications are all made possible by far-ultraviolet (UV) radiation. Because of their greater transparency and optical nonlinearity in the far-UV range, AlN and AlGaN materials have proven highly beneficial for applications involving wavelength conversion devices, thanks to their enormous bandgap energy reaching up to around 6.1 eV, or around 210 nm. We successfully demonstrated the 230 nm far-UV SHG in a vertical non-inverted AlN/AlGaN superlattice structure. The estimated bandgap energy was approximately 5.79 eV, and the bandgap energy difference between AlN and AlGaN in a superlattice structure was approximately 0.41 eV [IWN 2024]. The objective for developing a strained-layer superlattice (SLS) AlN/AlGaN non-inverted waveguide was to increase the bandgap difference inside the AlN/AlGaN SLS structure, which in turn enhanced piezoelectric polarization, thus modulating the d_{33} and third-order non-linear effects[1]

A sapphire substrate was used to grow an ultra-thin layer of AlN (<90 nm) that was prepared by sputtering and subsequent face-to-face annealing (SP-FFA). On top of this layer, an AlN/AlGaN SLS was grown using metal-organic vapor phase epitaxy (MOVPE). Based on the XRD results, the AlN layer is 4 nm thick, and the AlGaN layer is 2 nm thick. The AlN molar fraction in AlGaN was 78%. The waveguide has a thickness of ~270 nm to satisfy the modal dispersion phase matching condition between the fundamental wave of 458 nm for the TM00 mode and the second harmonic (SH) wave for the higher mode (TM02). The finite difference method determined the electric field distributions and effective refractive indices of the fundamental and SH-guided modes. Improving the piezoelectric polarization inside the SLS AlN/AlGaN directly affected the nonlinear optical coefficient $\chi^{(2)}_{eff}$. As a result, the nonlinear coupling coefficient kappa (k) was increased to 7.74 $W^{-1/2}$ cm^{-1} in this work. The higher value of kappa might be useful in reducing the length of the device. Furthermore, an SHG demonstration will be reported.

Reference:

Shin, W. J., Wang, P., Sun, Y., Paul, S., Liu, J., Kira, M.,. & Mi, Z. (2022). Enhanced Pockels effect in AlN microring resonator modulators based on AlGaN/AlN multiple quantum wells. ACS Photonics, 10(1), 34-42

OD-Tue-18B - Nonvolatile and reconfigurable two-terminal electro-optic duplex memristor based on III-nitride semiconductors

3. Optical devices

Ke Jiang*[1]
Zhiwei Xie[1], Shangli Zhang[1], Jianwei Ben[1], Mingrui Liu[1], Shunpeng Lv[1], Yuping Jia[1], Xiaojuan Sun*[1], Dabing Li*[1]
[1] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences

Abstract text: With the fast development of artificial intelligence (AI), Internet of things (IOT), etc, there is an urgent need for the technology that can recognize, store and process a staggering amount of information. AlScN has unique advantages due to its immense remnant polarization, superior temperature stability and good lattice-match to other III-nitrides. However, due to the large band-gap, strong coercive field, low photo-generated carrier generation and separation efficiency of the AlScN, it is difficult for itself to accumulate enough photo-generated carriers to induce polarization inversion, limiting its application in in-memory sensing and computing. To address this issue, an electro-optic duplex memristor on a AlScN/i-n GaN hetero-structure based Schottky diode is proposed. This two-terminal memristor shows excellent electrical and opto-electrical nonvolatility and reconfigurability. At both modes, the current on/off ratio can reach the magnitude of 10^4, and the resistance states can be effectively reset, written and long-termly stored. At electrical mode, the resistance state change originates from the ferroelectric polarization inversion of the AlScN in the hetero-structure, which influences the depletion region width and electron transport barrier height of the device. At opto-electrical mode, the memory window can be controlled by the illuminating light intensity due to the photocunductive effect of the i-GaN layer and the photo-generated carrier induced electron transport barrier reduction effect, which can regulate the partial bias applied to the AlScN layer. However, it is challenging to realize optical multi-state due to its limited light sensitivity for AlScN. Therefore, we further fabricate a AlScN/p-i-n GaN heterojunction optoelectronic synapse, overcoming the limitation by leveraging hole capture at the AlScN/p-GaN hetero-interface. The novel structure maintains excellent memristor characteristics, realizing an on/off ratio of over 9.36×10^5. More importantly, the device can mimic synaptic characteristics essential for artificial vision systems, achieving an image recognition accuracy of 93.7% with a weight evolution nonlinearity of 0.26. This approach not only extends the applications of AlScN in optoelectronics but also paves the way for advanced artificial vision systems with image preprocessing and recognition capabilities.

OD-Tue-19B* - Flexible and stretchable UV-LEDs based on core-shell GaN/AlGaN nanowires

3. Optical devices

Roberto Hernandez[1]
Fedor M. Kochetkov[2], Diana Kolesina[3], Nuno Amador-Mendez[1], Vladimir Neplokh[2], Vincent Grenier[4], Sylvain Finot[5], Lucie Valera[4], Jules Duraz[1], Etienne Herth[1], Sophie Bouchoule[1], François Julien[1], Malini Abraham[6], Subrata Das[6], Gwénolé Jacopin[5], Dmitry V. Krasnikov[7], Albert G. Nasibulin[7], Joël Eymery[4], Ivan S. Mukhin[2], Christophe Durand[4], Maria Tchernycheva[1]
[1] C2N-CNRS, Université Paris Saclay, 91120 Palaiseau, France
[2] Alferov University, Khlopina, 8/3, 194021 Saint Petersburg, Russia and Peter the Great St. Petersburg Polytechnic University, Polytechnicheskaya, 29, 195251 Saint Petersburg, Russia
[3] Alferov University, Khlopina, 8/3, 194021 Saint Petersburg, Russia
[4] Univ. Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, NPSC, 38000 Grenoble, France
[5] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France
[6] Materials Science and Technology Division, CSIR-National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram, Kerala 695019, India
[7] Kemerovo State University, Krasnaya Str. 6, Kemerovo 650000, Russia

Abstract text: Ultraviolet (UV) light sources find many applications, such as curing of different soft matters, plant growth, medical treatments including wearable devices, etc. For some of them flexibility and stretchability bring valuable advantages. Nanowires (NWs) thanks to their small cross-section are ideal active material for flexible LEDs. Moreover, their crystal quality exceeds that of thin films, which is particularly important in the UV domain where the material quality remains a major issue. Furthermore, nanowire geometry potentially enhances light extraction efficiency.

In this work, we present a demonstration of flexible UV-A and UV-B LEDs based on GaN NWs with core-shell GaN/AlGaN quantum wells embedded in n-p AlGaN junction finished by a p-GaN shell. The NWs were encapsulated into polymer matrices, contacted with single-walled carbon nanotubes (SWCNTs) patterned films acting as pixel electrodes. The NWs were grown by MOVPE on c-sapphire substrates, the cathodoluminescence and electroluminescence were first investigated on single wires [1,2]. Then, polymer-embedded NW composite membranes with a 1 cm2 area were fabricated. Their electroluminescence at low bias starts with a broad emission around 388 nm (3.195 eV) attributed to donor-acceptor pair recombination of p-GaN accompanied with a weak broad yellow band at 550 nm (2.25 eV) arising from defects in the GaN core. When the bias is increased, the QW UV emission appears at about 13 V and rapidly becomes dominant. This UV emission peaks from 3.54 eV (350 nm) to 4.1 eV (302 nm) depending on the radial GaN/AlGaN quantum well thickness and barrier content [3].

An optimization of the transparent flexible contact was performed: pre-stretched SWCNTs patterned into a meander shape were selected as the best flexible and stretchable contact to the UV membrane LEDs. Electrical stability was tested under cyclic loads in two directions up to 10% stretching, demonstrating that after a few cycles the SWCNTs meander electrodes adopt a configuration that is insensitive to stretching. The developed UV LEDs were tested as a source for luminophore and phosphor excitation producing orange and red luminescence, respectively [3]. This paves the way for flexible compact UV LEDs to be employed in sensing, detection of fluorescent labels or light therapy.

[1]10.1063/5.0101591
[2]10.1021/acsami.9b19314
[3]10.1021/acsami.4c06181

OD-Tue-20B - Monolithically-integrated GaN metasurface collimator mosaic for miro-light-emitting diodes

3. Optical devices

Chia-Yen Huang[1]
Yu-Min Chang[1], Po-Yang Chang[1], Teng-Li Shao[1], Yan-Hong Lin[1], Yi-Lin Yang[1], Yao-Wei Huang[1], Tien-Chang Lu[1]
[1] Department of Photonics, National Yang Ming Chiao Tung University, Hsinchu, Taiwan

Abstract text: III-nitride Micro light-emitting diode (μ-LED) has been regarded a candidate for next-generation display technologies such as augment-reality glasses due to its high luminous intensity and robustness. Recently, μ-LEDs are considered as the information carrier for co-packaged optics in data communication. However, as the distance among the chips is brought to proximity, the optical cross-talk to adjacent pixels has been a limiting factor for the overall performance at the module level. Therefore, it's critical to reduce the divergence angle of the emission pattern of the μ-LED by external packaging methods or integrated nanostructures.

GaN-based metasurface collimator (MC) is designed to tailor the spherical wavefront into the plane wave for the dipole emission on its focus. According to finite difference in time-domain (FDTD) simulations, the divergence angle in the far field can be reduced from Lambertian ~120 degrees to be less than 10 degrees, and the normal intensity is enhanced to more than 5 folds. However, dipoles are distributed randomly within the quantum wells and the actual effectiveness has to be evaluated experimentally. In this report, we integrated MC mosaics with different widths on the backside of the μ-LED epitaxy by sequential laser lift-off, electron-beam lithography, and dry-etching. Angle-resolved photoluminescence (PL) showed that the LED epi with 4 μm MC mosaic has a 2.9 times power enhancement along the normal direction than those without MC. However, that with 8 μm mosaic is only enhanced 1.2 times. The PL divergence angle was reduced by 24 degrees with the 4 μm MC mosaic but only 16 degrees with the 8 μm MC mosaic. We attributed the significant impact of the mosaic dimension to the effective collimating area for the MC and the active region. More detailed design methodology and future optimization strategies will be discussed during the conferences.

Growth mechanisms and models

2025-07-08
15:30 - 17:00
Growth mechanisms and models

GR-Tue-16 - Ab initio thermodynamics of III-nitride semiconductor surfaces: Improving the accuracy of predictions under growth conditions

1. Growth

Pawel Kempisty[1]
[1] Institute of High Pressure Physics PAS, Warsaw, Poland

Abstract text: Understanding the thermodynamics of nitride semiconductor surfaces is crucial for controlling growth and defect incorporation. However, many surface properties are inaccessible to direct experimental observation, making theoretical modeling essential. Density Functional Theory (DFT) is widely used to study surface reconstructions, adsorption, and impurity incorporation, but its conventional zero-temperature approach limits applicability to real growth conditions.
We improve ab initio thermodynamics by incorporating vibrational contributions via first-principles phonon calculations, enabling a more accurate determination of free energy, entropy, and chemical potential as functions of temperature and surface coverage. The surface free energy differs significantly from standard DFT energy, particularly for adsorbate-covered surfaces, leading to substantial changes in phase stability. We demonstrate how previously established surface phase diagrams are modified when vibrational contributions of adsorbates are considered [1].
We examine III-nitride surfaces under conditions relevant to Molecular Beam Epitaxy (MBE) and Metalorganic Vapor Phase Epitaxy (MOVPE), refining predictions under both metal-rich and ammonia-rich environments. By analyzing metal-covered surfaces, we achieve quantitatively accurate predictions for the MBE growth window, which opens when the adlayer transitions from a pseudo-crystalline to a liquid-like state [2]. We also explain differences in Si and Ge incorporation into GaN and InGaN during MBE growth by analyzing their chemical potential changes when adsorbed on metallic layers. Understanding the temperature- and coverage-dependent variations of surface free energy allows us to predict the stability of other adsorbates, such as As on GaN(0001) [3].
Using DFT, we found significant differences in adsorption and diffusion between Al and Ga lattice sites on AlGaN surfaces. We constructed potential energy surface maps to identify preferred adsorption sites and used the Nudged Elastic Band method to determine diffusion barriers and migration pathways, refining these properties at high temperatures relevant to AlGaN growth by MOVPE.

[1] P. Kempisty, Y. Kangawa, Physical Review B 100, 085304, 2019.
[2] P. Kempisty, K. Kawka, A. Kusaba, Y. Kangawa, Materials 16, 5982, 2023.
[3] M. Grodzicki, P. Kempisty, et al., Vacuum 233, 113956, 2025.

GR-Tue-17* - MBE growth of ultra-thin GaN/AlN quantum wells for cathodoluminescent UV lamps

1. Growth

Ettore Coccato[1]
Jesus Cañas[1], Alexis Palais[2], David Cooper[2], Névine Rochat[2], Edith Bellet Amalric[1], Eva Monroy[1]
[1] Univ. Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France
[2] Univ. Grenoble Alpes, CEA, LETI, 38000 Grenoble, France

Abstract text: UV lamp research focuses on two germicidal spectral ranges: 260-270 nm and 220-230 nm, with the latter being safer for humans. Mercury lamps (254 nm) remain the standard, while non-toxic alternatives like KrCl excimer lamps (222 nm) and AlGaN-based LEDs suffer from low efficiency, which promps interest in alternatives like cathodoluminescent lamps. These devices use a cold cathode-generated electron beam to excite a semiconductor active region, inducing radiative recombination.

Here, we present a study on 500-nm-thick stacks of ultra-thin GaN/AlN quantum wells (QWs) grown by plasma-assisted MBE on AlN-on-sapphire. The QW dimensions are tailored to cover the 280-230 nm spectral range. Results are compared with similar structures containing AlGaN/AlN quantum dots (QDs) [1].

The growth process begins with the deposition of 170 nm of n-type GaN, which helps dissipate charges and minimizes the formation of conical defects responsible for bimodal luminescence [2]. Then, a 45-period QW superlattice is deposited, with a period consisting of 1-5 monolayers (MLs) of GaN and 8.8 nm of AlN. A growth interruption under N flux is introduced after the deposition of AlN to consume the Al excess. For the GaN layers, the Ga excess evaporates during the growth of the following AlN layer.

Our results highlights the critical role of the substrate temperature in the radiative performance of QWs. Optimal conditions are achieved at approximately 720°C, the ideal growth temperature for GaN. Higher temperature induce triangular cracks, leading to spectral broadening. Furthermore, to ensure a planar surface morphology during the growth of AlN barriers, it is essential to maintain an Al/N ratio greater than 1.2.

By reducing GaN deposition time, we obtained thinner QWs, with the emission shifting from 380 to 230 nm as thickness approaches 1 ML. Cathodoluminescence (CL) measurements indicate that the internal quantum efficiency (IQE) increases as the QW thickness decreases, reaching a maximum for 1 ML QWs. QWs emitting at 300 nm exhibit distinct TE polarization, whereas those emitting at 236 nm do not display any preferred polarization. In the disinfection range, the power efficiency of QWs and QDs appears to be comparable. Regarding light polarization,

[1] Cañas et al. *ACS Photonics* 10, 4225 (2023); [2] Cañas et al. *ACS Nano* 18, 11886 (2024).

GR-Tue-18 - Improvement of 2DEG Properties in Pseudomorphic AlN/GaN/AlN heterostructures grown by Metal-Organic Vapor Phase Epitaxy

1. Growth

Akira Yoshikawa[1]
TaeGi Lee[1], Sho Sugiyama[1], Manabu Arai[2], Jun Suda[2], Hiroshi Amano[2]
[1] Asahi Kasei
[2] Nagoya University

Abstract text: Recently, AlN-based electron devices have attracted significant attention due to the large breakdown electric field and high thermal conductivity of AlN. Pseudomorphic AlN/GaN/AlN heterostructures grown on high-quality AlN substrates take advantage of the low dislocation density and enhanced 2DEG carrier density, making them ideal for power or RF HEMTs. While the Cornell University group has successfully grown AlN/GaN/AlN structures using MBE [1], adopting MOVPE is more suitable for industrial applications. Our group has recently reported the pseudomorphic growth of 21-nm-thick GaN on AlN (0001) substrates using MOVPE [2], as well as the 2DEG characteristics of AlN/GaN/AlN heterostructures grown [3]. However, pseudomorphic growth was only achieved when using very small miscuts of less than 0.1°, whereas larger miscuts led to lattice relaxation. Moreover, smaller miscuts tend to induce island-like growth, which may degrade the 2DEG characteristics. Therefore, achieving pseudomorphic growth on substrates with larger miscut angles is crucial for improving 2DEG quality.

In this study, we focused on optimizing the growth conditions of the AlN buffer layer. It was found that reducing the buffer layer growth temperature to 950°C resulted in an waving step structure on the surface. By growing an AlN (9 nm)/GaN (12 nm) heterostructure on this AlN buffer layer under the same conditions as our previous study, we successfully achieved pseudomorphic growth even on substrates with larger miscut angles such as 0.2°. Comparative analysis of Hall-effect measurements on samples with different miscut angles revealed that substrates with larger miscut angles exhibited superior 2DEG properties. Furthermore, while we previously used tri-methyl gallium (TMGa) for growth, we speculated that tri-ethyl gallium (TEGa) might offer advantages in terms of impurity reduction and therefore switched the precursors. As a result, in combination with optimized miscut angles, Hall-effect measurements at room temperature showed an electron mobility of 528 cm^2/Vs, a sheet carrier concentration of 2.3×10^{13} cm^{-2}, and a sheet resistance of 507 Ω/sq. These results demonstrate the strong potential of MOVPE growth for AlN/GaN/AlN heterostructures.

[1] Y. Chen *et al.*, APL **125,** 142110 (2024).
[2] A. Yoshikawa *et al.*, JJAP **63,** 060903 (2024).
[3] A. Yoshikawa *et al.*, J. Appl. Phys. submitted.

GR-Tue-19 - How does diffusion impact high-Al content AlGaN barriers in MOCVD-grown GaN HEMTs?

1. Growth

Alexis Papamichail[1]
Axel R. Persson[1], Ingemar Persson[1], Jonas Johansson[2], Vallery Stanishev[1], Nerijus Armakavicius[1], Minho Kim[1], Steffen Richter[1], Philipp Kühne[1], Per O. Å. Persson[1], Plamen P. Paskov[1], Niklas Rorsman[3], Vanya Darakchieva[4]
[1] Competence Center for III-Nitride Technology, C3NiT-Janzén, Department of Physics, Chemistry and Biology (IFM), Linköping University, 581 83 Linköping, Sweden
[2] Solid State Physics and NanoLund, Lund University, 221 00 Lund, Sweden
[3] Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-41296 Göteborg, Sweden
[4] Competence Center for III-Nitride Technology, C3NiT-Janzén, Solid State Physics and NanoLund, Lund University, 221 00 Lund, Sweden

Abstract text: AlGaN/GaN high electron mobility transistors (HEMTs) are essential components in high-power and high-frequency applications. These capabilities are driven by HEMT device scaling technologies which enable high electron density of the two-dimensional electron gas (2DEG) and short gate-to-channel distance, achieved through use of high-Al-content ultra-thin barrier layers. The barrier layer plays a crucial role on the HEMT transport properties. However, precisely controlling its thickness and composition remains challenging due to the diffusion effects at the elevated temperatures of metalorganic chemical vapor deposition (MOCVD) [1]. Uncontrolled Ga/Al redistribution results in deviations in barrier thickness and composition, interface blurring and ultimately, degradation of the 2DEG properties.

In this work, we develop the growth process for ultrathin (sub-10 nm) and high Al-content (up to 80%) AlGaN barrier GaN HEMT structures by hot-wall MOCVD. Advanced characterization involving scanning transmission electron microscopy (STEM) and energy-dispersive X-ray spectroscopy (EDS), enable experimental determination of the Al profiles revealing deviations from the intended structures with Al content of 50%, 70% and 100%. Furthermore, numerical simulations of Al diffusion processes occurring during growth and cooling, highlighted the impact of high-temperature kinetics and reactor memory effects on the final barrier composition profile. By combining the experimental observations with the results from Lehighton and terahertz optical Hall effect (THz-OHE) [2] measurements, we critically analyze and discuss the implications of Al-profile deviations on the 2DEG properties and device performance.

1. Papamichail *et al.,* Appl. Phys. Lett. 125, 123505 (2024).
2. Armakavicius *et al.,* Materials 17, 3343 (2024).

GR-Tue-20 - Limitations of distributed polarization doping using in AlGaN-based deep-ultraviolet laser diode structures by their cracking during growth

1. Growth
Mikhail Rudinsky[1]
Kirill Bulashevich[1], Olga Soboleva[1]
[1] Semiconductor Technology Research d.o.o. Beograd, Belgrade, Serbia

Abstract text: One of the challenges in development of AlGaN-based deep-ultraviolet (DUV) laser diodes (LDs) is the improvement of hole supply into the active region [1]. The only effective method to overcome this problem so far is the use of distributed polarization doping (DPD) based on compositionally-graded AlGaN layers.
The DPD is commonly used in practically all DUV LD structures. However, limitations of this approach are studied in insufficient detail. Growth of the DPD layers inevitably results in mismatch stress, which can be relaxed via cracking, thus deteriorating the device performance. Here, we present a study of limitations for DPD approach due to possible cracking, considering state-of-the-art DUV LD structures [2,3].
For estimation of cracking probability, we use the stress intensity factor (SIF) approach [4]. By cracking, we imply the mode I crack channeling [5], producing a cracks network, covering the whole growth surface. We simulate the epitaxy of the structures, calculating evolution of maximum SIF as a function of crack depth and comparing it with the critical value. Exceeding the SIF critical value means cracking of the structure.
Two LD structures were described in [2]: a non-optimal Sample 1 and optimized Sample 2. Authors of [2] adjusted the composition of DPD-layer by band-diagram modeling, and experimentally obtained a strong improvement of the device efficiency and output power, explaining the result by electronical reasons only. Our simulations predict cracking of the DPD-layer in Sample 1, in contrast to Sample 2. So, cracking can also be a reason for deterioration of LD performance and should be considered during structure optimization.
Investigation of the structure from [3] shows, that it was well-optimized, regarding its potential cracking. The maximum SIF for this structure is close, but does not exceed critical value. Based on the structure design, we have examined its sensitivity to variations of thicknesses and compositions of various layers. The applied approach can be also helpful for optimization of DPD layers in DUV light-emitting diodes.

[1] M. Iwaya et al., Jpn. J. Appl. Phys. 61, 040501 (2022)
[2] R. Kondo et al., Appl. Phys. Lett. 121, 253501 (2022)
[3] T. Omori et al., Appl. Phys. Express 13, 071008 (2020)
[4] A. Romanov et al., Int. J. Mat. Res. 98, 8, 723 (2007)
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UV Lasers and LEDs with enhanced carrier injection

2025-07-08
15:30 - 17:00
UV Lasers and LEDs with enhanced carrier injection

OD-Tue-16A - Low-Threshold Current (~25 mA) AlGaN-Based UV-B Laser Diodes Utilizing Refractive Index Waveguide Structures on Lattice-Relaxed AlGaN

3. Optical devices

Motoaki Iwaya[1]
Takumu Saito[1], Rintaro Miyake[1], Ryota Watanabe[1], Sho Iwayama[1], Satoshi Kamiyama[1], Tetsuya Takeuchi[1], Hideto Miyake[2], Koichi Naniwae[3]
[1] Meijo University, Nagoya, Japan
[2] Mie University, Tsu, Japan
[3] Ushio, Inc., Gotenba, Japan

Abstract text: UV-B light (wavelength: 280–315 nm) has numerous applications, including the treatment of skin diseases. In particular, there is a strong demand for the development of compact, highly efficient, high-output AlGaN laser diodes. We have successfully achieved room-temperature pulsed lasing by utilizing high-quality, lattice-relaxed AlGaN crystals and applying polarization doping to the p-type AlGaN cladding layer. Additionally, our recent studies have revealed that enhancing the abruptness of the heterointerface between the electron blocking layer and the p-side optical waveguide layer improves carrier injection efficiency. However, compared to visible GaInN-based laser diodes operating in the violet, blue, and green regions, UV-B AlGaN-based laser diodes still face challenges, particularly high threshold currents.

In this study, we investigated the fabrication and evaluation of refractive-index-waveguided UV-B AlGaN-based laser diodes with a ridge structure designed to enhance lateral optical confinement. Theoretical calculations using the equivalent refractive index method indicated that etching down to the vicinity of the active layer effectively strengthens lateral optical confinement. However, a trade-off was observed: as the etching depth approached the active layer, the proportion of non-functional devices exhibiting current leakage increased significantly. Within the experimental scope, it was suggested that stopping the etching near the interface between the p-side optical waveguide layer and the electron blocking layer was optimal, balancing both superior device characteristics and high laser oscillation yield.

Based on these findings, we fabricated a prototype laser diode under the optimized conditions. A prototype laser diode with an optimized structure successfully achieved pulsed lasing at a threshold current of 25 mA (corresponding to a threshold current density of 3.1 kA/cm²) at room temperature in a device with a 300-μm-cavity-length without edge coating. This represents a remarkably low threshold current for the UV-B region, comparable to that of visible violet, blue, and green GaInN-based laser diodes. Furthermore, near-field analysis experimentally confirmed that the ridge structure significantly improved lateral optical confinement. In this presentation, we will discuss these device characteristics in detail.

OD-Tue-17A* - Optimizing Heterointerfaces for Enhanced Carrier Injection Efficiency in AlGaN-based UV-B Laser Diodes

3. Optical devices

Takumu Saito[1]
Rintaro Miyake[1], Shundai Maruyama[1], Yusuke Sasaki[1], Shogo Karino[1], Seiya Kato[1], Naoki Kitta[1], Ryota Watanabe[1], Yuma Miyamoto[1], Sho Iwayama[1], Hideto Miyake[2], Koichi Naniwae[3], Satoshi Kamiyama[1], Tetsuya Takeuchi[1], Motoaki Iwaya[1]
[1] Meijo University, Nagoya, Japan
[2] Mie University, Tsu, Japan
[3] Ushio, Inc., Gotenba, Japan

Abstract text: The performance of AlGaN-based deep UV laser diodes (LDs) has been improving, but their carrier injection efficiency (η_i) remains low at ~10%, far below that of visible and infrared LDs [1,2]. Additionally, the characteristic temperature (T_0) of UV-C LDs is ~107 K [2], less than half that of visible LDs, indicating poor carrier confinement. Simulations suggest that a steep and large AlN mole fraction difference of 0.55 between the p-side waveguide layer and the electron-blocking layer (EBL) in the UV-B LD could enhance η_i to ~90% [3]. However, solid-phase diffusion may unintentionally form a graded AlN mole fraction layer at these interfaces. While low-temperature growth has been reported to mitigate this [2-4], the impact of graded layer thickness and AlN mole fraction differences on UV-B LD performance remains unclear. This study investigated these effects.

We fabricated five UV-B LD samples (lasing wavelength of ~302 nm) with graded layer thicknesses of 2, 5, 9, 15, and 29 nm by fixing the AlN mole fraction difference between the EBL and p-side waveguide layer at 0.55 and adjusting growth conditions. The graded layer thickness was measured using Z-contrast scanning transmission electron microscopy. η_i was estimated from the reciprocal dependence of external differential quantum efficiency on cavity length. T_0 was determined from the change in threshold current when the device temperature was varied between 10°C and 70°C.

The analysis results showed η_i values of 22%, 18%, 23%, 7%, and 9% for graded layer thicknesses of 2, 5, 9, 15, and 29 nm, respectively. Reducing the graded layer thickness from 29 nm to 2 nm increased η_i, demonstrating that η_i in UV-B LD exceeding 20% can be achieved experimentally. A reduction in threshold current density was also observed. Furthermore, for 2 nm, T_0 reached 208 K, comparable to that of blue LDs (150–300 K), indicating that enhancing the heterojunction barrier between the EBL and p-side waveguide layer is highly effective. However, discrepancies between experimental and simulated η_i values suggest room for further improvement, requiring additional verification.

[1] R. Kondo *et al.* Appl. Phys. Lett. **121**, 253501(2022).

[2] Z. Zhang *et al.* Appl. Phys. Lett. **124**, 061109 (2024).

[3] T. Saito *et al.*, Phys. Status Solidi A (under review).

[4] T. Saito *et al.*, Appl. Phys. Lett. (in print).

OD-Tue-18A - Nanoscopic Insights into the Structural and Optical Properties of a Far-UVC-LED: Detailed Characterization of Carrier Capture in Active Region

3. Optical devices

Frank Bertram[1]
Gordon Schmidt[1], Peter Veit[1], Juergen Christen[1], M. Ajmal Khan[2], Kohei Fujimoto[3], Yuya Nagata[3], Hiroyuki Yaguchi[4], Hideki Hirayama[2]
[1] Institute of Physics, Otto-von-Guericke-University Magdeburg, Germany
[2] RIKEN Cluster for Pioneering Research, Saitama, Japan
[3] RIKEN Cluster for Pioneering Research, Saitama, Japan / Saitama University, Saitama 338-8570, Japan
[4] Saitama University, Saitama 338-8570, Japan

Abstract text: Deep ultraviolet AlGaN-based UV-LEDs emitting below 250 nm have attracted much attention for their wide applications. In the UV spectral range, especially in the deep-UV 200 – 250 nm, low hole injection efficiency brought on by a confluence of high Mg activation energy and limited hole mobility in the p-AlGaN layer as well as control over non-radiative recombination channels pose major challenges. A comprehensive characterization on nanoscale to address each individual layer with a detailed analysis of the carrier transport is required to further understand and improve such devices.

The UVC-LED under study was grown by MOVPE on a 4 µm thick AlN template on sapphire. Subsequently to an undoped $Al_{0.86}Ga_{0.14}N$ buffer (about 500 nm thick), a 1.7 µm thick Si-doped n-$Al_{0.86}Ga_{0.14}N$ layer follows. The active region consist of a 4-fold UV MQW (1 nm $Al_{0.94}Ga_{0.06}N$ barrier with 3.5 nm $Al_{0.86}Ga_{0.14}N$ well), a 6 nm $Al_{0.94\rightarrow0.86}Ga_{0.06\rightarrow0.14}N$ spacer and a 9 nm thick p-AlN electron blocking layer. The LED is completed by a 75 nm p-$Al_{0.9}Ga_{0.1}N$ layer and finally a p-GaN layer (75 nm thick) on top, both layers heavily Mg-doped (10^{20} cm^{-3}).

A direct one-by-one correlation of the optical properties with the real structure of the far-UV-LED emitting at 228 nm is presented using low temperature cathodoluminescence spectroscopy (CL) directly performed in a scanning transmission electron microscope (STEM) to determine the local defect density, composition homogeneity - especially the in-plane Al uniformity in the Al-rich AlGaN layers - strain distribution, and impurity incorporation on nanometer scale. In particular, we focus on the capture of excess carriers in the active region as well as the identification of non-radiative recombination mechanisms.

Cross-sectional CL linescans across the active region reveal the characteristic emission of the individual layers: the n-$Al_{0.86}Ga_{0.14}N$ layer exhibits an intense emission at 226 nm, whereas the p-$Al_{0.9}Ga_{0.1}N$ shows only weak luminescence at much shorter wavelength (λ = 214 nm). The subsequent following p-GaN is highly Mg-doped yielding to a donator-acceptor pair (DAP) band above 395 nm. The UV-MQW emits at a wavelength of λ = 230 nm. The vertical capture of excess carriers into the UV-MQW is comprehensively characterized.

OD-Tue-19A* - Precise determination of the charge concentration in linearly graded AlGaN distributed polarization doped layers of 233 nm light emitting diodes

3. Optical devices

Marcel Schilling[1]
Franz Biebler[1], Thibaut Ehlermann[1], Paula Vierck[1], Massimo Grigoletto[2], Jakob Höpfner[1], Bernd Witzigmann[3], Tim Wernicke[1], Michael Kneissl[2]
[1] Institute of Solid State Physics, Technische Universität Berlin, Berlin, Germany
[2] Institute of Solid State Physics, Technische Universität Berlin, Berlin, Germany; Ferdinand-Braun-Institut (FBH), 12489 Berlin, Germany
[3] Lehrstuhl für Optoelektronik, Department EEI, Friedrich-Alexander-Universität, Erlangen-Nürnberg, Germany

Abstract text: Ultraviolet-C light emitting diodes with emission wavelengths shorter than 240 nm (far-UVC LEDs) are suitable for skin-safe UVC antisepsis [1]. However, the poor *p*-type conductivity of Mg-doped AlGaN impedes the hole injection in far-UVC LEDs. Therefore, distributed polarization doping (DPD) of AlGaN has been explored to circumvent the high ionization energies of impurity doping [2]. The present study investigates the impact of DPD layers employed as hole injection layer with different thicknesses (25 – 150 nm) on the net concentration of polarization charges *N* (corresponding to the hole concentration) and the external quantum efficiency (EQE) of far-UVC LEDs with a peak emission wavelength of 233 nm. All LED heterostructures were grown by metalorganic vapour-phase epitaxy and included a p-type AlGaN DPD layer with a linear composition grading from AlN to $Al_{0.8}Ga_{0.2}N$. Capacitance-voltage (CV) and electroluminescence (EL) measurements were carried out to determine the depletion width *w, N* and EQE. The charge carrier profiles reveal three different regions. In the first region ($w <$ DPD thickness) *N* is constant and corresponds to the charge carrier concentration of the DPD layer. In the second region ($w \approx$ DPD thickness) *N* exhibits a minimum, originating from the transition to the lower band gap *p*-GaN:Mg layer. Lastly, in the third region ($w >$ DPD thickness) *N* corresponds to the doping concentration of the *p*-GaN:Mg contact layer. Evaluating *N* in the first region yields an increase in *N* from $(9.7 \pm 0.5) \times 10^{17}$ cm^{-3} for the 150 nm thick DPD to $(2.5 \pm 0.1) \times 10^{18}$ cm^{-3} for the 50 nm thick DPD. At the same time the peak EQE (cw, on-wafer) increased from 0.19 % for the LED with a 150 nm thick DPD to 0.3 % for the LED with a 25 nm thick DPD. The increase of *N* can be explained by the stronger composition gradient for thinner DPDs leading to a higher polarization charge *N*. Simulations show that a higher *N* for thinner DPDs leads to a higher current injection efficiency which explains the increase in EQE. This study shows that distributed polarization doping of AlGaN is a promising alternative compared to conventional Mg doping for efficient *p*-type conductivity and that CV measurements are suitable for the determination of *N*.

[1] Glaab *et al*., *Sci. Rep.*, **11**, 14647 (2021) [2] J. Simon et al., *Science* **327**, 60-64 (2010)

OD-Tue-20A - Polarisation Assisted n-AlGaN Electron Injection Layer in 229 nm far-UVC LEDs for Hole Blocking and Current Density Enhancement

3. Optical devices

Muhammad Ajmal Khan[1]
Hiromitsu Sakai[2], M. Nawaz Sharif[1], Yuya Nagata[3], Kohei Fujimoto[3], Amina Yasin[1], Mitsuhiro Muta[4], Yasushi Iwaisako[4], Hiroyuki Yaguchi[3], Hideki Hirayama[1]
[1] RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[2] Shin-Etsu Chemical Co., Ltd. Japan
[3] Saitama University, Saitama 338-8570, Japan
[4] Nippon Tungsten Co., Ltd., Minoshima 1-2-8, Hakata-ku, Fukuoka-shi 812-0017, Japan

Abstract text: An AlGaN-based 230 nm far-ultraviolet-C (far-UVC) light-emitting diode (LED) is safe to be used in manned environments against viruses, bacteria, and fungi. However, the external-quantum efficiency (EQE) of far-UVC LEDs is quite low due to the hole leakage, electron leakage, and low carrier injection efficiency into MQWs. Such hole leakage or electron leakage can promote non-radiative recombination channels and pose major challenges in the Al-rich far-UVC LEDs.

In this work, a new polarisation-assisted n-AlGaN Electron Injection Layer (EIL) on the n-side (n-PA) of far-UVC LED was investigated both theoretically and experimentally to generate 3D electron density. The n-PA based LED under study was grown by MOVPE on a 4 μm thick AlN template on c-plane sapphire. Subsequently, heteroepitaxy of undoped $Al_{0.86}Ga_{0.14}N$ buffer (500 nm thick), a 1.7 μm thick Si-doped n-$Al_{0.86}Ga_{0.14}N$ buffer layer, and a 30 nm-thin n-side polarisation-assisted (n-PA) n-$Al_{0.86\rightarrow0.97}Ga_{0.14\rightarrow0.03}N$ EIL were grown. The quantum well consists of a 4-fold QW (1 nm $Al_{0.94}Ga_{0.06}N$ barrier with 3.5 nm $Al_{0.86}Ga_{0.14}N$ well), a 6 nm ud-$Al_{0.94\rightarrow0.86}Ga_{0.06\rightarrow0.14}N$ final barrier and a 9 nm thick p-AlN electron blocking layer. The LED is completed by a 75 nm p-$Al_{0.9}Ga_{0.1}N$ layer and finally a p-GaN layer (75 nm thick) on top, both layers heavily Mg-doped (10^{20} cm^{-3}). Our previous reference LED was similar to the n-PA LED, except for the Flat n-AlGaN EIL part.

When Al-deposition is started from Ga-face crystals and graded from low Al composition (0.86) to high Al composition (0.97) in n-AlGaN EIL, the polarisation bound charge is positive, and it induces the generation of mobile 3D electrons. As a result, the EQE and light output power of the polarized far-UVC LED on-wafer under continuous-wave operation at RT was enhanced to 0.22% and 1.2 mW. More interestingly, the emission wavelength was pulled toward a shorter of 229 nm, and also the operating voltages were reduced in the n-PA LED. The new n-PA based LED has been investigated theoretically using the SiLENSe simulation model. It was observed that the hole current density leakage toward the n-side was remarkably suppressed when compared to the conventional flat n-AlGaN EIL-based LED. Finally, quite improved carrier injection efficiency (CIE) of 58% (n-PA LED) was observed, when compared to the referenced structure having a CIE of 29% (Flat n-AlGaN EIL LED).

Plenary 3

2025-07-09
08:00 - 08:40
Plenary 3

Cracking the Code of GaN Crystal Growth: Advances, Challenges, and the Road Ahead

1. Growth

Michal Bockowski[1]
[1] Institute of High Pressure Physics Polish Academy of Sciences

Abstract text: This lecture provides a comprehensive overview of GaN crystallization, exploring its history, current advancements, and future technological directions. GaN has revolutionized the semiconductor industry, enabling breakthroughs in optoelectronics and high-power, high-frequency electronic devices. The discussion will trace the evolution of GaN crystal growth, highlighting key milestones, recent progress, and future prospects.

Various growth techniques will be examined, including halide vapor phase epitaxy (HVPE), high-nitrogen-pressure solution (HNPS) growth, the sodium flux (Na-flux) method, and acidic and basic ammonothermal methods. Presently, GaN crystallization is dominated by the Na-flux and HVPE methods, along with derivatives such as halide-free vapor phase epitaxy (halide-free VPE) and oxide vapor phase epitaxy (oxide VPE), as well as ammonothermal processes.

Among these, the ammonothermal method—originally proposed by Dwilinski—remains the most promising. A comparative analysis of acidic and basic ammonothermal growth will highlight their advantages, limitations, and technological challenges. While ammonothermal GaN yields high-quality crystals, optimizing growth rates and material quality remains an ongoing challenge. The integration of ammonothermal and HVPE technologies offers significant potential, despite existing hurdles. The lecture will also examine the properties of HVPE-GaN grown on ammonothermal GaN substrates and explore the Na-flux method's role in seed production for ammonothermal growth.

Scaling GaN crystal growth for commercial applications remains a critical challenge. The development of larger ammonothermal autoclaves and advanced seed growth techniques is essential, with 6- and 8-inch GaN wafers dependent on further advancements in ammonothermal scalability. The lecture will outline the current progress and realistic timelines for these developments.

Finally, the transition from bulk crystal growth to usable substrates requires precise processing techniques, including wafer cutting and surface treatment. The lecture will conclude by discussing key applications of GaN substrates in optoelectronic and electronic devices, such as high-power vertical transistors and laser diodes.

Plenary 4

2025-07-09
08:40 - 09:20
Plenary 4

Epitaxy of Transferrable III-Nitrides on Two-Dimensional Materials

1. Growth

Fang Liu[1]
Yucheng Guo[1], Zexing Yuan[1], Zhaoying Chen[1], Tao Wang[2], Ping Wang[1], Hailin Peng[3], Xin-Zheng Li[1], Bo Shen[1], **Xinqiang Wang**[1]
[1] School of Physics, Peking University, Beijing 100871, P. R. China
[2] Electron Microscopy Laboratory, School of Physics, Peking University, Beijing 100871, P. R. China.
[3] College of Chemistry and Molecular Engineering, Peking University, Beijing 100871, P. R. Chi

Abstract text: The integration of III-nitride semiconductors with two-dimensional (2D) materials presents transformative platforms for next-generation hybrid optoelectronic systems, yet the epitaxy of wafer-scale transferrable III-nitride films with simultaneously high uniformity and low threading dislocation density remains a critical challenge. Here, we demonstrate a quasi-van der Waals epitaxy (quasi-vdWE) strategy using engineered 2D material buffer layers to achieve 4-inch transferrable single-crystal GaN films, highly uniform green light-emitting diodes (LEDs), and ultra-dense vertical micro-LEDs. We reveal that interfacial bonding hybridization—covalent interactions synergized with weak vdW forces—critically governs GaN crystallinity: the quasi-vdWE regime enforces in-plane crystallographic registry, enabling single-crystalline growth, whereas pure vdW or remote epitaxy regimes yield polycrystalline films due to insufficient interfacial interaction. By manipulating the atomic configuration at GaN/2D heterointerfaces, we achieve selective nucleation and growth of metal-polar or nitrogen-polar GaN domains on graphene and h-BN, providing a versatile platform for both film growth and device fabrication. Furthermore, replacing transferred few-layer graphene (≤3 monolayers, MLs) with epitaxial graphene (≥3 MLs) and introducing growth mode regulation during metalorganic chemical vapor deposition (MOCVD) triggers dislocation bending and annihilation, reducing threading dislocation densities in metal-polar GaN films from 3×10^9 cm^{-2} to 2×10^8 cm^{-2}. These advances resolve the crystal quality-transferability paradox in quasi-vdWE, establishing that epitaxial 10-ML graphene buffer layers provide atomically continuous and weakly coupled interfaces for high-quality GaN growth while maintaining mechanical strippability. This breakthrough enables the fabrication of 4-inch strippable green LED epiwafers with excellent wavelength uniformity (σ<1 nm) and ultra-dense micro-LED arrays (6,350 pixels per inch, 2-μm pixel size) operating at 1×10^8 nit brightness. Our work bridges atomic-scale interface control with wafer-scale manufacturing, paving the way for production of transferrable III-nitride films, which hold significant promise for applications in ultrahigh-resolution displays and next-generation optoelectronic devices.

Plenary 5

2025-07-09
09:50 - 10:30
Plenary 5

Deep Ultraviolet Edge-Emitting Lasers: Progress and Prospects

3. Optical devices

Maki Kushimoto[1]
Z. Zhang[2], A. Yoshikawa[2], K. Aoto[1], A. Honda[1], L. J. Schowalter[1], C. Sasaoka[1], H. Amano[1]
[1] Nagoya University, Nagoya, Japan
[2] Nagoya University, Nagoya, Japan & Asahi Kasei, Tokyo, Japan

Abstract text: Deep ultraviolet (DUV) edge-emitting lasers have garnered significant attention due to their potential applications in sterilization, precision material processing, and optical communication. While remarkable progress has been made, further advancements in device performance are essential to unlock their full potential. Key challenges remain, including enhancing electrical conductivity, improving crystal quality, and minimizing fabrication-induced defects. In particular, the impact of polarization-induced effects in AlGaN-based heterostructures has become a critical factor in device design, requiring new approaches to carrier injection and recombination management.

This talk will discuss recent progress in optimizing DUV laser device characteristics, with a focus on heterostructure design, carrier injection efficiency, and defect management. Through the development of laser diodes, we have demonstrated the effectiveness of polarization-enhanced doping techniques, which has drawn significant attention to polarization-based device designs. This has led to broader applications beyond lasers, as exemplified by our recent demonstration of high-voltage PN diodes utilizing polarization doping for both n- and p-type layers. These findings highlight the potential of polarization engineering in wide-bandgap semiconductor devices, paving the way for next-generation power electronics and optoelectronic components.

As we move forward, continuous advancements in material engineering and device design will be crucial not only for the practical realization of DUV lasers but also for the broader development of next-generation photonic and electronic devices. These efforts are expected to drive innovations in high-power, long-lifetime devices across a wide range of wavelengths, expanding the frontiers of semiconductor technology. By further exploring the polarization effects, defect control, and novel device architectures, we aim to establish a foundation for future breakthroughs in both optical and electronic applications.

Acknowledgement

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Novel nitrides-new approaches

2025-07-09
10:40 - 11:55
Novel nitrides-new approaches

GR-Wed-1 - Growth of hexagonal BN crystals by traveling-solvent floating zone

1. Growth

Eli Zoghlin[1]
Juliette Plo[2], Gaihua Ye[3], Cynthia Nnokwe[3], Reina Gomez[4], Austin Ferrenti[5], Satya Kushwaha[6], Rui He[3], Stephen Wilson[4], Pierre Valvin[2], Bernard Gil[2], Guillaume Cassabois[2], James Edgar[7], Tyrel McQueen[8]
[1] William H. Miller III Department of Physics and Astronomy, The Johns Hopkins University, Baltimore 21218, Maryland, United States
[2] Laboratoire Charles Coulomb, Université de Montpellier and CNRS, Montpellier 34095, France
[3] Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, Texas 79409, United States
[4] Materials Department, University of California Santa Barbara, Santa Barbara 93106, California, United States
[5] Department of Chemistry, The Johns Hopkins University, Baltimore 21218, Maryland, United States
[6] Department of Chemistry, The Johns Hopkins University, Baltimore 2
[7] Tim Taylor Department of Chemical Engineering, Kansas State University, Manhattan 66506, Kansas, United States
[8] Department of Chemistry, The Johns Hopkins University, Baltimore

Abstract text: Hexagonal-BN (h-BN) stands out as a nitride workhorse in the world of two-dimensional (2D) materials, finding immense application as a passive component in devices (e.g., as a substrate for other 2D materials), while also providing useful active capabilities (e.g., as an optically hyperbolic material for mid-IR photonics). The most demanding experiments involving h-BN utilize bulk crystals. Although these samples provide the highest purity and crystallinity their size (≈ 1 mm × 1 mm × 0.1 mm) is a limitation and current growth techniques lack scalability. Therefore, to fully realize the various capabilities of h-BN, substantial improvements in bulk crystal growth capabilities are required. Particularly important is the development of methods which increase bulk crystal size while also further reducing the concentration of extrinsic impurities and structural defects. The characteristics of the traveling-solvent floating-zone (TSFZ) technique – a crucible-free instantiation of directional solidification – make it appropriate for addressing these issues, provided a compatible flux can be found. While the established Ba-B-N-based flux for h-BN growth is incompatible with TSFZ due to the GPa level pressures required, recent advances have demonstrated that high-quality crystals can be grown from transition metal fluxes (e.g. FeCr). This opens the possibility of applying TSFZ to h-BN. Here, we explore the potential of this technique to improve the state of bulk h-BN crystal growth with respect to purity, structural perfection, and crystal size. We present an investigation of a wide range of growth parameters – including flux composition, gas pressure, and growth geometries – which, guided by efficient first-pass characterization by X-ray tomography, has led to the first growth of h-BN crystals via TSFZ. The resulting crystals are characterized by a variety of standard techniques, including Raman and photoluminescence spectroscopy, demonstrating comparable structural perfection in parallel with improved purity. This discovery begins an exciting new area of development for bulk crystal growth of h-BN with the potential to conquer many of the existing challenges related to fully exploiting its potential.

GR-Wed-2* - Above band gap illumination during III-nitrides growth by plasma-assisted molecular beam epitaxy

1. Growth

Karolina Peret[1]
Mikołaj Chlipała[1], Anna Nowakowska-Szkudlarek[1], Henryk Turski[2]
[1] Institute of High Pressure Physics "Unipress" Polish Academy of Sciences, Warsaw, Poland
[2] Institute of High Pressure Physics "Unipress" Polish Academy of Sciences, Warsaw, Poland; School of Electrical and Computer Engineering, Cornell University, Ithaca, USA

Abstract text: Ability to change majority carrier type by doping differentiates semiconductors to other material classes. In the wide bandgap semiconductors such as GaN, dependence of the formation energies of charged defects on the Fermi energy is notable. In p-type layers doped with Mg only a 1% of the incorporated Mg atoms generate holes at room temperature, so to achieve high density of holes very high amount of dopants is needed, which leads to creation of compensating point defects including Mg self-compensation [1,2].

It has been shown that above band gap illumination (ABGI) during growth of GaN:Mg thin films by metalorganic vapour-phase epitaxy (MOVPE) enables control over formation of point defects. It changes concentration of unintentional point defects such as H, O and possibly nitrogen vacancies (V_N) by modifying their formation energies. Also Mg ions are no longer compensated by H introduced during growth, which eliminates the cause for post-growth annealing and leads to enhanced p-type conductivity [1,3].

In this work we report on ABGI during plasma-assisted molecular beam epitaxy (PAMBE), which is a hydrogen-free technique. The 360 nm laser with output power of 200 mW as a source of illumination, was applied through collimator mounted on a UV-transparent viewport of the reactor. We investigated visible LED structures where ABGI was introduced during p-type layers growth. In the interest of creating polarization induced hole-doping with high carrier concentration, we decided to use a Mg-doped graded AlGaN. Two sets of LEDs were prepared: the first one with and without ABGI during growth in the AlGaN layer, doped with Mg and the second one without any p-type doping.

We show that by introducing Mg doping into graded AlGaN layers we increase operating voltage of these devices similarly to reports for MOVPE-grown LEDs [4]. Based on the electroluminescence measurements we show that ABGI during PAMBE growth prevents compensation from oxygen or intrinsic point defects/complexes, resulting in remarkably lower operating voltage for examined samples, while maintaining similar wavelengths and power outputs.

[1] M. P. Hoffmann, et al., 2014, *Proc. SPIE*

[2] Cai X., et al., 2022, *Phys. Rev. B*

[3] Z. Bryan, et al., 2013, *J. Electron. Mater.*

[4] K. Sato, et al., 2021, *Applied Physics Express*

GR-Wed-3 - A New Member in III-Nitride Family: Wurtzite Aluminium Arsenide Nitride

1. Growth

Xu Yang[1]
Hiroshi Amano[1], Markus Pristovsek[1]
[1] Nagoya University, Nagoya, Japan

Abstract text: Alloying of transition metals (such as Sc and Y) into AlN has attracted attention because such alloys can be lattice-matched to GaN while providing higher polarization-induced two-dimensional electron gas (2DEG) densities compared with the conventional AlGaN/GaN heterostructures in high electron mobility transistors. However, the growth with metalorganic vapor phase epitaxy (MOVPE) is challenging because of the low vapor pressures of the available sources of Y and Sc.

As a possible alternative, we investigated MOVPE growth of wurtzite aluminum arsenic nitride (AlAsN). For arsenic, there are three proven precursors AsH_3, trimethylarsine, and tertiarybutylarsine (tBAs) with high vapor pressures. According to our calculations, 8% As in $AlAs_yN_{1-y}$ can be lattice-matched to GaN and would result in approximately twice the 2DEG density compared to $Al_{0.3}Ga_{0.7}N$/GaN. The 2DEG density would even exceed that of AlP_yN_{1-y}/GaN pioneeringly reported by our group with similar strain conditions.

Despite these merits, no reports exist of $AlAs_yN_{1-y}$. Thus, this study investigated the fundamental growth process of AlAsN by MOVPE on GaN/sapphire templates using tBAs, TMAl, and NH_3 as precursors. To explore the full parameter space, AlAsN/GaN heterostructures were grown on semi-insulating GaN/sapphire templates. We settled for high V/III ratios as we did not observe significant As-on-Al anti-site formation even with high tBAs or NH_3 flows. This is because there are no stable As-N compounds and hence no gas phase reactions. In comparison, the strong reaction between NH_3 and P precursors during the growth of AlP_yN_{1-y} led to a high density of P-on-Al antisite defects when increasing P or N partial pressure. Instead, we found growth temperature is important for As incorporation. By lowering the temperature, more As incorporates into $AlAs_yN_{1-y}$ due to reduced As desorption from the surface. For instance, the As content of $AlAs_yN_{1-y}$ decreases from ~ 2% at 700°C to nearly zero at 800°C. So far, AlAsN with ~ 1.2% As exhibited the best sheet resistance of 1288 ohm/sq., indicating the formation of 2DEG at the AlAsN/GaN interface. However, surface roughness and probably point defects in AlAsN need further study for better electrical properties.

GR-Wed-4* - Exploring yttrium aluminum nitride: growth, characterization, and insights into its physical properties

1. Growth

Niloofar Afshar[1]
Mohamed Yassine[2], Ali Yassine[3], Oliver Ambacher[4]
[1] Power Electronics, Institute for Sustainable Systems Engineering INATECH, University of Freiburg, Emmy-Noether-Str. 2, D-79110 Freiburg, Germany
[2] mohamed.yassine@inatech.uni-freiburg.de
[3] ali.yassine@inatech.uni-freiburg.de
[4] oliver.ambacher@inatech.uni-freiburg.de

Abstract text: Alloy systems of transition metal nitrides exhibit remarkable properties, making them highly promising for diverse applications. Among these, ScAlN has emerged significant attention due to its enhanced piezoelectric coefficient and ferroelectric behavior[1][2]. Inspired by the atomic similarities of Y and Sc, theoretical studies predict that YAlN could exhibit even superior potential in piezo-acoustic applications[3][4], which is due to the predicted higher stability of YAlN in wurtzite structure at high alloy concentrations, up to $x = 0.75$[3]. However, experimental studies on YAlN are limited, leaving critical gaps in understanding this material system.
This work focuses on sputter growth of high-quality wurtzite YAlN thin films and their structural, optical, and electrical characterization. It was observed that strain in basal plane has significant impact on the structural quality of YAlN. This approach was studied using low-concentration YAlN as a buffer layer to support higher-concentration layers, effectively reducing strain. This method proved successful, as the formation of wurtzite-phase films up to $x = 0.37$ yttrium concentration was observed[5]. At higher concentrations, formation of amorphous YAlN was observed. The corporation of Y atoms in the films was proved by band gap measurements, but no specific crystal structure could be identified for the films. Using the combination of band gap, x-ray diffractometry, and AFM measurements, it was speculated that amorphization of YAlN before reaching the theoretical phase transition is one of the main limitations of stabilizing wurtzite structure at high alloy concentrations. This behavior was not predicted by theoretical studies and was not observed in similar alloy, ScAlN.
Future efforts aim to achieve higher Y concentrations by engineering growth methods and stabilizing the wurtzite phase. Understanding the structural phase transition of YAlN and further enhancing its structural quality is an important step in advancing our understanding of this promising material system and its potential for next generation device application.

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Detectors

2025-07-09
10:40 - 11:55
Detectors

OD-Wed-1 - Enhancing the efficiency in solar cells based on AlInN/a-Si/Si(100) Heterojunction Solar Cells: impact of AlInN Layer Thickness and Al Content

3. Optical devices

Michael Sun[1]
Miriam Cadenas[1], Sirona Valdueza-Felip[1], **Fernando B. Naranjo**[1]
[1] Photonics Engineering Group, University of Alcala, 28871, Alcalá de Henares, Spain.

Abstract text: Recent advancements in III-nitride-based solar cells show that incorporating an amorphous silicon (a-Si) buffer layer enhances the interface quality and photovoltaic efficiency of III-nitride on Si heterojunctions. This study reviews the strategies used to enhance the efficiency of solar cells based on this kind of heterojunctions and examines the influence of the AlInN thickness and Al content on the structural, electrical, and optical properties of n-AlInN/a-Si/p-Si(100) heterojunction solar cells to optimize their photovoltaic performance.

Structures were fabricated by reactive RF sputtering, with an a-Si buffer layer of 15 nm deposited at 550°C and 30W (DC) [1]. AlInN layers with different thickness (80, 130, 230, and 330 nm, corresponding to samples E80, E130, E230 and E330) were grown at the same temperature under pure N_2, with RF powers of PIn = 30W and PAl = 125W. Structural characterization via X-ray diffraction confirmed crystalline wurtzite phase with no phase separation, yielding an Al mole fraction of ~0.31. Optical transmittance spectroscopy indicated a bandgap energy ~2.1 eV.

Solar cells with an active area of ~0.7 cm^2 were fabricated, with 120 nm-thick Al top and bottom contacts deposited by DC sputtering at 100W and 75W, respectively. Current-voltage characteristics were measured under dark and AM1.5G solar illumination (1000 W/m^2). As the layer thickness increases, the open-circuit voltage (Voc) and fill factor (FF) initially improve, reaching a peak efficiency of 2.1%. However, for E230, a slight trade-off between Voc and short-circuit current density (Jsc) leads to a minor efficiency drop. In the thickest device, E330, further efficiency loss occurs due to the reduced light transmission of the AlInN, that reduces the amount of light reaching the depletion region close to the silicon substrate. This optical loss limits the carrier generation, ultimately decreasing the efficiency of the device.

This study highlights the critical role of the III-nitride thickness for optimizing the performance of AlInN/a-Si/Si(100) heterojunction solar cells, providing valuable insights for further development of III-nitride-based photovoltaic devices.

[1] M. Sun et al. Mat. Sci. Semicon. Proc., 176, 108321, 2024
Financial support was provided by RELY project (MICIU/AEI/10.13039/501100011033 Next Generation EU/ PRTR) with ref PDC2023-145888-I00.

OD-Wed-2 - The Influence of GaN Substrates on the Performances of GaN-based Ultraviolet Avalanche Photodetectors

3. Optical devices

Davide Balzerani[1]
Zhiyu Xu[1], Alexandra Dolgashev[1], Nepomuk Otte[2], Theeradetch Detchprohm[1], Subhra Chowdhury[3], Dhrubes Biswas[3], **Russell Dupuis**[1]
[1] School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, USA
[2] School of Physics, Georgia Institute of Technology, Atlanta, USA
[3] Magnolia Optical Technologies, Woburn, USA

Abstract text: GaN-based *p-i-n* photodiodes can provide enhanced UV light detection. One important variable to understand is the impact of the quality of the native-GaN substrate. In this work, we present data on top-illuminated ultraviolet Avalanche Photodiodes (APDs) with Shallow Bevel Mesas (SBMs) edge termination, grown by metalorganic chemical vapor deposition on three different (0001) *n*-type GaN substrates with threading dislocation densities < 1E6 cm^{-2}. Substrate A is a free-standing (FS) GaN substrate grown by hydride vapor phase epitaxy (HVPE). Substrate B is a FS GaN substrate derived from HVPE growth on ammonothermal (AM) bulk GaN seeds. Substrate C is an AM-GaN substrate. 1 µm *n*-GaN ([*n*]=5E18 cm^{-3}), followed by 350 nm multiplication layer of GaN:*uid* ([*n*]~2E16 cm^{-3}), 295 nm *p*-GaN ([*p*]=7E17 cm^{-3}), and 25 nm p^+-GaN ([Mg]=1E20 cm^{-3}) contact layer were grown simultaneously on the three substrates in a CCS 6x2" reactor.

The APDs were fabricated with SBM edge termination to suppress the sidewall leakage current [1]. Multi-step lithography followed by thermal reflow of the photoresist pattern above 200°C was implemented to form SBM masks. Cl_2/BCl_3-based inductively coupled plasma etching was used to transfer the patterned photoresist design to the GaN surface around the device mesas. To reduce the absorption loss in the *p*-layer, 150 nm-deep recessed windows were etched into the *p*-GaN. The devices were passivated with spin-on glass.

The reverse *J-V* characteristics of 60 µm diameter devices show low leakage current densities below 10^{-9} A/cm^2 for reverse biases up to 57%, 64%, and 67% of the respective breakdown voltages (BVs) of -105 ± 1.5, -107 ± 0.2, and -110 ± 0.1 V for devices on Substrate A, B and C respectively. At 1 A/cm^2 the maximum gains of 2.1 x 10^5, 2.6 x 10^5, and 3.5 x 10^5 were derived under 360nm illumination, while they are 1.6 x 10^6, 1.8 x 10^6, and 9.1 x 10^6 under 280nm for Substrates A, B, and C, respectively.

At room temperature, the devices exhibit average peak photoresponse at zero bias of 167, 137, and 187 mA/W at λ =352-354 nm on Substrate A, B, and C respectively. The respective peaks of 174, 147, 207 mA/W correspond to external quantum efficiencies (EQEs) of 64%, 51% and 76%. These photo response peaks are 40-45% higher than those of the control devices without recessed windows.

[1] Z. Xu, et al., *IEEE Electron Dev. Lett.,* **71**, 3761 (2024).

OD-Wed-3 - Wrinkle-Free Hexagonal Boron Nitride for Flexible Deep-Ultraviolet Photodetectors

3. Optical devices

Yiwei Duo[1]
Junxi Wang[1], Jinmin Li[1], **Tongbo Wei**[1]
[1] Research and Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

Abstract text: Hexagonal boron nitride (h-BN) has emerged as a promising material for electronics, optoelectronics, and flexible devices owing to its dangling-bond-free surface, high optical absorption efficiency, and exceptional mechanical strength. However, epitaxial growth of h-BN on heterogeneous substrates introduces significant interlayer strain, resulting in surface wrinkling in thicker films and severely compromising carrier mobility and film stability. In this work, we demonstrate that interlayer strain serves as the intrinsic driving force for wrinkle formation in h-BN, rendering the films metastable. As interlayer strain accumulates proportionally with h-BN thickness, the surface morphology transitions sequentially through three distinct regimes: wrinkle-free flat surfaces, micro-wrinkles, and spontaneous exfoliation. By characterizing the interlayer stress distribution in h-BN and simulating the stress accumulation process, we identify the critical thicknesses for different morphologies and propose a mechanism for wrinkle formation and evolution. Interlayer strain progressively weakens the van der Waals interactions between h-BN and the substrate. As strain accumulates beyond a critical threshold, localized regions decouple from the substrate, forming micro-wrinkles that partially relieve the accumulated strain. However, the continued buildup of stress enlarges the wrinkle dimensions, ultimately leading to spontaneous exfoliation that fully releases the residual strain. By leveraging selective wet etching of the sapphire/h-BN epitaxial interface using hydrofluoric acid, we demonstrate the successful transfer of a pristine, wrinkle-free 4 nm h-BN film and the fabrication of high-performance flexible deep-ultraviolet photodetectors. At 30 V and a light power density of 10.82 $\mu W/mm^2$, the detector achieves a responsivity of 1.72 mA/W, a specific detectivity of 2.72×10^{12} Jones, and on-off ratio of 10^3, with a response time in the millisecond range. This work advances the fundamental understanding of strain engineering in h-BN and offers a pathway for developing flexible and multifunctional devices.

OD-Wed-4 - AlGaN based detectors for the UVC and VUV spectral region

3. Optical devices

Ronny Kirste[1]
Pramod Reddy[2], Will MeCouch[2], Seiji Mita[2], Ramon Collazo[3], Zlatko Sitar[3]
[1] North Carolina State University, , Raleigh, USA & Adroit Materials Inc., Raleigh, USA
[2] Adroit Materials Inc., Raleigh, USA
[3] North Carolina State University, Raleigh, USA

Abstract text: Detectors with sensitivity in the UVC and VUV regions are desired for many applications, including UV Raman spectroscopy and atmospheric observations. Detectors based on Al-rich (Al > 70%) AlGaN offer the potential to detect UV light (<270 nm) while remaining blind to VIS/IR light without the need for additional filters (solar blindness).

In this presentation, recent progress in the development of AlGaN-based UV detectors is discussed. The presented devices were grown on AlN substrates. It is found that using AlN, in contrast to other substrates such as sapphire or Si, enables larger device areas and excellent performance. The reduction of threading dislocations achieved with native AlN is crucial for minimizing impurity incorporation, which is necessary for achieving low dark currents. However, it is also shown that hillocks, often observed during AlGaN/AlN growth, are detrimental to device operation.

By adjusting the Al content—and consequently the bandgap—AlGaN-based detectors offer tunable sensitivity in the 230–270 nm range while naturally extending into the VUV. They effectively reject solar emission, and compared to SiC-based devices, they provide an orders-of-magnitude improvement in visible light rejection. Typical VIS/UV light rejection rates exceeding 10^7 can be achieved without additional filters. For photons with energies exceeding the bandgap of the absorption region, quantum efficiencies surpassing 70% are demonstrated, while in the VUV region, the efficiency drops (due to the increasing bandgap of AlGaN) to 30–50%.

Devices can be operated as simple detectors or as APDs. In the latter case, Geiger-mode operation and gain exceeding 10^5 are demonstrated. It is found that the growth conditions and impurity levels in the absorption/multiplication region drastically impact dark count rates. A reduction in carbon levels in the multiplication region leads to a four- to fivefold decrease in dark counts (1000 cps). Finally, the potential of 1D and 2D arrays is discussed. Finally, it is shown that AlGaN-based detectors can be arranged in arrays for spectroscopy applications.

In summary, recent advances in the development of AlGaN-based UV detectors grown on native AlN substrates are discussed. The results highlight their potential for various applications, offering tunable sensitivity in the UVC and VUV range along with high quantum efficiencies.

Power Electronics 3 (Reliability)

2025-07-09
10:40 - 11:55
Power Electronics 3 (Reliability)

ED-Wed-A1 - Leakage Current Suppression by Reducing Embedded Grains in GaN-on-Si Wafers for Improving Reliability of Power Devices

4. Electronic devices

Ryoma Kaneko[1]
Jumpei Tajima[1], Seiya Takeda[1], Akira Yoshioka[2], Toshiki Hikosaka[1]
[1] Corporate Research & Development Center, Toshiba Corporation, Komukai-Toshiba-cho, Saiwai-ku, Kawasaki, Japan
[2] Toshiba Electronic Devices & Storage Corporation, Komukai-Toshiba-cho, Saiwai-ku, Kawasaki, Japan

Abstract text: Development of large-diameter GaN-on-Si wafers is essential technology for achieving low-cost GaN power devices. The GaN-on-Si wafers are designed with complex epitaxial layers to mitigate stress and dislocation caused by lattice mismatch between Si substrate and GaN crystal. Towards further cost reduction of GaN-on-Si substrates, we are developing substrates based on step-graded AlGaN buffer layers. The growth rate of our step-graded AlGaN buffer layers was 1.5 times higher than that of conventional AlN/AlGaN superlattices buffer layer. However, we also found that the rapidly grown GaN-on-Si substrates tend to show low yield due to catastrophic breakdown when high voltage is applied through the substrates.

In this study, we report a comprehensive analysis of macroscopic defects which cause the leakage current through GaN epitaxial layers, using multiple GaN-on-Si wafers with different layer structure and growth conditions. AlGaN/GaN-HEMT structures including AlGaN step-graded buffer layers were grown on 200 mm diameter Si substrates by MOCVD. By using a cross-sectional TEM analysis of a leakage spot, which was determined by emission microscope (EMS) method, grains embedded in V-pit were observed in the AlGaN buffer layer. In addition, it is found that the embedded grains tend to form in the early stages of AlGaN buffer layer with low crystal quality. The electron diffraction images of the observed grains display clear but low symmetric patterns. Comparing the obtained diffraction pattern with the simulation, it is confirmed that the embedded grains consist of single crystals whose *c*-axis is inclined relative to that of a normal crystal. By suppressing pyramidal hillocks on the AlGaN surface through crystal growth at high temperature, we have succeeded suppressing the grains significantly. As a result, leakage current was greatly suppressed and a high breakdown voltage of over 1000 V was obtained for more than 90% of the samples in GaN-on-Si wafer with high-speed growth. This result indicates that reducing the promotion of the embedded grains in the buffer layer is important for high reliability of GaN-on-Si power devices.

This work is based on results obtained from a project, JPNP21029, subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

ED-Wed-A2 - Suppression of hole injection into near-interface traps by inserting AlN interfacial layer between AlSiO and GaN

4. Electronic devices

Masamichi Akazawa[1]
Masanobu Takahashi[1], Kenji Itoh[2], Tetsuo Narita[3]
[1] Research Center for Integrated Quantum Electronics, Hokkaido University, Sapporo, Japan
[2] Toyota Central R&D Labs., Inc., Nagakute, Japan and Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan
[3] Toyota Central R&D Labs., Inc., Nagakute, Japan

Abstract text: GaN metal-oxide-semiconductor (MOS) field-effect transistors (FETs) are suitable for power systems with high current capability and high voltage. Interface states and near-interface traps (NITs) can deteriorate channel carrier mobility and/or the stability of a GaN MOSFET. Here, we report that the influence of NITs on holes at an AlSiO/GaN interface can be controlled by inserting an AlN interfacial layer (IL).

MOS samples were formed on an n-type GaN (n-GaN) epitaxial layer grown by metalorganic vapor phase epitaxy on an n^+-GaN substrate. An AlN IL was formed on n-GaN by plasma-enhanced atomic layer deposition (PEALD). For comparison, a sample without an AlN IL was also prepared. An AlSiO layer was formed by alternating ALD of Al_2O_3 and SiO_2 monolayers followed by annealing to merge them. The thickness of the AlN IL was 0.8 nm. Finally, gate and ohmic electrodes were formed. The fabricated MOS samples were investigated by sub-bandgap-light-assisted capacitance–voltage (*C–V*) measurements. In these measurements, monochromatic sub-bandgap light was illuminated on MOS samples under a deep-depletion bias with the surface Fermi level at around 1.9 eV below the conduction band edge (E_C) for 6 s, and *C–V* measurements were conducted after turning off the light.

The hysteresis in the dark *C–V* curves was mainly attributed to the injection of electrons into interface traps near E_C and was reduced by inserting the AlN IL [1]. The sub-bandgap light can excite electrons to the E_C of GaN, resulting in the hole capture by deep interface states. The *C–V* characteristics of the sample without the AlN IL showed photoinduced negative voltage shifts at the flat-band capacitance, which increased with photon energy. These voltage shifts increased monotonically and did not saturate with irradiation time, which cannot be explained merely by the behavior of interface states and indicated that trapped holes were injected into NITs. By inserting the AlN IL, we were able to drastically suppress the voltage shift caused by hole injection. Thus, it can be predicted that the AlN IL suppresses the hole injection into NITs even at the AlSiO/p-GaN interface in the dark.

This work was supported by the MEXT program (Grant No. JPJ009777).

[1] T. Narita et al., Phys. Status Solidi RRL **18**, 2400141 (2024).

ED-Wed-A3 - Suppression of current collapse in N-polar GaN HEMTs with polarization-charge-controlled recess gate structures

4. Electronic devices

Akihiro Hayasaka[1]
Shigeki Yoshida[1], Junya Yaita[1], Akira Mukai[1], Junji Kotani[1], Kozo Makiyama[1], Ken Nakata[1]
[1] Transmission Devices Laboratory, Sumitomo Electric Industries, Ltd., Yokohama 244-8588, Japan

Abstract text: N-polar GaN HEMTs with a back barrier that reduces short-channel effects have attracted significant interest. In N-polar HEMT structures, the GaN channel layers are located near the surface, which also leads to improved gate control. However, a lower potential barrier between the two-dimensional electron gas (2DEG) and the surface may result in severe current collapse compared to Ga-polar HEMTs. In this study, we discuss the mechanism of the suppression of current collapse in N-polar GaN HEMTs by employing recessed gate structures.
N-polar GaN HEMT with and without recessed MIS-gate structures were fabricated in this study. For planar and recessed MIS-HEMTs, cap layers of AlGaN and AlGaN/GaN/AlGaN were employed on the GaN channel layer, respectively. For both structures, the MIS gate consisted of $HfSiO_x$ gate dielectrics. The 2DEG density in the access regions were measured to be 1.9×10^{13} cm^{-2} and 1.8×10^{13} cm^{-2} for the planar and recessed gate structures, respectively. Current collapse was evaluated through pulsed IV measurements to clarify the effect of the recessed gate structure. The current reduction rates under Idq = 8 mA/mm and Vd = 40 V stress were found to be 19% for the planar gate and 4% for the recessed gate, indicating successful suppression of current collapse in the recessed gate structure.
To clarify the reasons for the improvement in current collapse in the recessed gate structure, C-V measurements were conducted. For the recessed MIS-HEMT, a second plateau region was observed near the 0 V region in the C-V curve, clearly indicating the presence of free carriers within the GaN cap layer. These results suggest that the existence of free carriers, i.e., 2DEG in the GaN cap layer can effectively suppress current collapse in N-polar GaN HEMTs. In the case of the planar gate structure, electron traps at the surface directly affect the electron flow in 2DEG channel, resulting in current collapse. In the recessed gate structure, we believe that electron traps at the surface are effectively screened by the 2DEG in GaN cap.
Our findings indicate that the employment of the recessed gate structure plays a key role in the suppression of current collapse in N-polar GaN HEMTs. We believe that control of 2DEG density in GaN cap layer and precise design of the band structure is essential to unleash the full potential of N-polar GaN HEMTs.

ED-Wed-A4 - Minimization of Negative Bias Instability in GaN-based MOSFETs by Inserting Thinner AlN Interlayer at AlSiO/p-type GaN Interface

4. Electronic devices

Hiroko Iguchi[1]
Tetsuo Narita[1], Kenji Ito[1], Shiro Iwasaki[1], Emi Kano[2], Nobuyuki Ikarashi[2], Kazuyoshi Tomita[2], Daigo Kikuta[1]
[1] Toyota Central R&D Labs., Inc., Nagakute, Aichi, Japan
[2] Nagoya University, Nagoya, Aichi, Japan

Abstract text: Threshold voltage (V_{th}) stability is one of the critical issues for GaN-based metal-oxide-semiconductor field-effect transistors (MOSFETs). We have recently demonstrated that a high channel mobility over 170 $cm^2\ V^{-1}\ s^{-1}$ with high V_{th} stability against gate positive bias stress can be obtained via inserting a thin crystalline AlN interlayer (AlN-IL) formed by plasma-enhanced atomic layer deposition at an AlSiO/*p*-type GaN interface [1]. Recently, the formation of hole traps at MOS interfaces have been identified [2], which may affect a negative bias instability (NBI) of V_{th}. Thus, in this study, we investigated the impacts of AlN insertion on the NBI.

A gate voltage of V_{th} −5 V was applied to the fabricated MOSFETs with an AlN-IL thickness of 0−3.8 nm for 3974 s as a negative bias stress. V_{th} shift was suppressed from −0.34 V to −0.24 V by inserting a 0.8-nm-thick AlN-IL. The spatial separation between GaN and AlSiO by inserting a thin crystalline AlN-IL would inhibit hole injection into oxide traps in the AlSiO. However, the V_{th} shift increased with increasing AlN-IL thickness.

We evaluated "reverse" split capacitance-voltage (*C*-*V*) characteristics for each MOSFET [3]. When a negative bias was applied, the capacitance was fixed without reaching the oxide capacitance, indicating that the surface potential in p-type GaN was strongly pinned due to hole traps at the MOS interface [2]. The hole trap level for each MOSFET with AlN-IL estimated from the Terman method was located at 1 eV above the valence band maximum, suggesting that the interfacial condition was the same regardless of the AlN-IL thickness.

The band diagrams estimated from the *C*-*V* characteristics suggested that holes were accumulated at the AlSiO/AlN interface during the NBI tests due to the polarization field in AlN. The hole accumulation at the AlSiO/AlN interface may be minimized by inserting an AlN-IL as thin as possible, resulting in the suppression of the NBI. As a result, both positive and negative bias instability can be suppressed by inserting a thinner AlN-IL at an AlSiO/*p*-type GaN interface in a GaN-based MOSFET with high channel mobility.

This work was supported by the MEXT Program (Grant no. JPJ009777).

[1] H. Iguchi *et al.*, Appl. Phys. Lett. 125, 022104 (2024). [2] H. Mizobata *et al.*, Appl. Phys. Express 16, 105501 (2023). [3] T. Narita *et al.*, Appl. Phys. Lett. 124, 103504 (2024).

Novel Electronic Devices 1 (Materials)

2025-07-09
10:40 - 11:55
Novel Electronic Devices 1 (Materials)

ED-Wed-B1 - Diamond and GaN Integration: Top-Side to All-Around Approaches

4. Electronic devices

Srabanti Chowdhury[1]
[1] Stanford University, Stanford, CA, USA

Abstract text: The relentless push for higher power density in computing, RF electronics, and high-performance systems has created an urgent need for innovative thermal management solutions. While
advancements in chip packaging have improved heat dissipation, fundamental thermal bottlenecks remain due to complex multi-layered material stacks and low-thermal-conductivity dielectrics, which restrict heat flow from active devices. Conventional cooling strategies, often reliant on distant heat sinks, struggle to efficiently extract heat from within these dense architectures, ultimately limiting device performance and long-term reliability. To address these challenges, our research has focused on a fundamentally different approach — spreading heat directly at its source. Since 2016, we have developed a low-temperature (400–500°C) growth process for polycrystalline diamond (PCD), enabling its direct integration near active device regions without compromising device integrity [1]. Through careful control of the sp^3:sp^2 bonding ratio, we achieved high thermal conductivities (300–650 W/m·K) in the grown diamond films, approaching theoretical limits for PCD of comparable thickness [1]. Furthermore, by incorporating phonon-mixing interlayers such as SiC, we demonstrated ultra-low thermal boundary resistance (TBR ~1.89 m^2K/GW), verified by molecular dynamics simulations that revealed phonon density-of-states (DOS) mixing can push TBR values below conventional diffuse mismatch model (DMM) predictions[2-4] This technology has been successfully demonstrated in GaN High Electron Mobility Transistors (HEMTs), achieving over a 70°C reduction in peak channel temperature at power densities of 25 W/mm, significantly enhancing device efficiency and reliability[5].

Most recently, we reported the first successful integration of low-temperature, all-around PCD heat spreaders on a 150 nm gate-length N-polar GaN RF MISHEMT platform for X-band applications. This process combined optimized diamond growth at 500°C with a thermally stable molybdenum gate metal and an MOCVD-grown SiNx gate dielectric. The resulting device demonstrated a drain saturation current of 0.96 A/mm and an ON/OFF ratio of 10^5. This work marks the first post-fabrication all-around diamond integration on an N-polar GaN HEMT platform, paving the way for improved thermal management and power efficiency in future RF electronics [6].

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ED-Wed-B2 - Suppressed self-heating effects in GaN HEMTs on polycrystalline diamond layers synthesized on backplates

4. Electronic devices

Hazuki Tomiyama[1]
Yoshiki Nishibayashi[2], Marina Takeuchi[2], **Naoteru Shigekawa**[1], Jianbo liang[1]
[1] Osaka Metropolitan University, Sakai, Japan
[2] Sumitomo Electric Industries, Ltd., Itami, Japan

Abstract text: GaN-on-diamond configurations are promising for realizing low-thermal-resistance GaN devices because of high thermal conductivity of diamonds. We previously fabricated GaN HEMTs on freestanding single crystalline as well as polycrystalline diamonds (PCDs) and demonstrated that the thermal properties and device characteristics of such on-diamond HEMTs outperformed those of on-Si HEMTs with the same layer structures and same geometries [1, 2].

In this work, we investigated the possibility of ~50-μm PCD layers synthesized on ~3-mm backplates (BPPCDs) as lower-cost substitutes for freestanding diamonds. We transferred nitride heterostructures grown on Si (111) substrates to BPPCDs and subsequently fabricated on-BPPCD HEMTs using the surface-activated bonding technology. We also fabricated on-Si HEMTs composed of the same heterostructures as reference. An on-BPPCD HEMT with gate length/width of 10 μm/50 μm revealed a ≈×1.2 larger maximum transconductance and a less apparent on-state negative differential conductance than those of an on-Si HEMT with the same geometry. We measured the spatial variation of temperature on surfaces of biased on-BPPCD and on-Si HEMTs using the micro-photoluminescence method. The thermal resistance of an on-BPPCD HEMT with gate width of 300 μm, which was defined as the change in the surface temperature at its drain edge of gate contact (hot spot) due to the power dissipation, was ≈×0.5 of that of an on-Si HEMT with the same geometry. The surface temperature in a region next to the channel of biased on-BPPCD HEMTs decreased to room temperature steeply regardless of their gate widths, which was in good contrast to the spatial variation of temperature in the vicinity of on-Si HEMTs and implied that on-BPPCD HEMTs were able to be placed closer to each other while keeping their temperature rise low. These results imply that GaN-on-BPPCD structures are promising for realizing nitride devices with suppressed self-heating effects in terms of their thermal resistance, device characteristics, as well as density of integration with low cost.

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[2] C. Moriyama, et al., presented in LTB-3D 2024 (31P-14).

ED-Wed-B3 - High Al content AlGaN channel high electron mobility transistors with top-side diamond integration for thermal management

4. Electronic devices

James S. Lundh[1]
Katie R. Gann[1], Brianna A. Klein[2], Tatyana Feygelson[1], Andrew A. Allerman[2], GlenAsia Gonzalez[2], Emma G. Rocco[1], Daniel J. Pennachio[1], Hannah N. Masten[1], Alan G. Jacobs[1], Andrew M. Armstrong[2], Marko J. Tadjer[1], Bradford B. Pate[1], Karl D. Hobart[1], Michael A. Mastro[1]
[1] U.S. Naval Research Laboratory, Washington, DC, United States
[2] Sandia National Laboratories, Albuquerque, NM, United States

Abstract text: The success of AlxGa1-xN/GaN high electron mobility transistors (HEMTs) has led researchers to transition this technology to realize AlyGa1-yN/AlxGa1-xN HEMTs to take advantage of the higher predicted critical field strengths of AlGaN alloys. However, AlGaN has much lower thermal conductivity (κ) than GaN and AlN due to disordered alloy scattering. As a result, exacerbated device self-heating is expected in AlGaN-based devices, and thermal management is critical in the device design process to successfully deploy next-generation power electronics. To address this, we have demonstrated top-side diamond integration with high Al content AlGaN channel HEMTs to improve thermal performance.
The Al0.70Ga0.30N channel and Si-doped Al0.85Ga0.15N barrier were grown by metal organic chemical vapor deposition (MOCVD) on AlN/sapphire templates. Ohmic contacts were formed by regrowth of a compositionally reverse-graded n+ epilayer, followed by deposition and annealing of Ti/Al/Ni/Au. Finally, Ni/Au was deposited for the gate electrode. Diamond growth was achieved using microwave plasma CVD. Next, a thin SiN layer was grown via plasma-enhanced CVD to protect the device surface during diamond growth, followed by a low temperature (500°C) diamond growth to accommodate this “diamond-after-gate” process. Although the film was only ~250 nm thick, the grain size was measured to be up to ~300 nm using atomic force microscopy (AFM). From Raman measurements, a sharp peak was observed at ~1330 cm-1, indicating high quality sp3-bonded carbon. From DC electrical characterization of the diamond-coated HEMTs, OFF-state leakage was measured to increase after the diamond growth. Thermoreflectance imaging was used to measure the average gate temperature rise from uncapped and diamond-capped devices; the device-level thermal resistance at the gate was measured to decreased ~30% due to the integration of top-side diamond.

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ED-Wed-B4* - Diamond p-Type Lateral Schottky Barrier Diodes with High Breakdown Voltage (4612 V at 0.01 mA/mm)

4. Electronic devices

Zhuoran Han[1]
Keith Chang[1], Can Bayram[1]
[1] Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, IL, USA

Abstract text: Diamond p-type lateral Schottky barrier diodes (SBDs) with a 2-μm-thick drift layer are fabricated with and without Al_2O_3 field plates. Schottky contacts composed of Mo (50 nm) / Pt (50 nm) / Au (100 nm) showed a barrier height of 1.02 ± 0.01 eV and ohmic contacts of Ti (30 nm) / Pt (30 nm) / Au (100 nm) achieved a specific ohmic contact resistance of 1.25 $\pm 0.98\times10^{-4}$ Ω-cm^2. Their forward and reverse bias characteristics are studied in detail. Both SBDs, with and without Al_2O_3 field plates, exhibit rectifying ratios larger than 10^7 at room temperature, and a peak current density of 5.39 mA/mm under 40 V forward bias at 200 °C. The leakage current density at room temperature is stable at approximately 0.01 mA/mm for both diodes. The SBD without the Al_2O_3 field plate exhibited a breakdown voltage of 1159 V, while the SBD with the Al_2O_3 field plate is stable under a reverse voltage of 4612 V, which is higher than many diamond SBDs previously reported.

The fabrication of the SBDs starts with a 2 μm p^- drift layer ([B] < 8×10^{15} cm^{-3}]) that was grown on a 3 × 3 mm^2 Type Ib (100) HPHT diamond substrate. Then, 200 nm p^+ diamond ([B] ~ 3×10^{20} cm^{-3}]) was selectively grown to form the ohmic contact region. Ohmic metal contacts were formed by e-beam evaporation, followed by thermal annealing at 450 ºC in an ambient of Ar gas for 50 minutes. Next, a 300 nm Al_2O_3 field plate was deposited by e-beam evaporation, followed by a lift-off process. The exposed diamond surface was ozone-treated at room temperature for 1.5 hours to obtain a stable oxygen termination prior to the Schottky contact deposition. The lateral SBD without the field plate broke down at 1159 V when the leakage current drastically increased to the compliance limit of 50 μA. The SBD with the field plate exhibited stable leakage current up to 4612 V—the limit of the experimental setup. The leakage current density at 4612 V reverse bias is less than 0.01 mA/mm, which is similar to that of the SBD without the field plate prior to breakdown. This work exhibits a higher breakdown voltage in the SBD with Al_2O_3 field plates than previously reported pseudo-vertical and vertical SBDs, lateral MESFETs, MOSFETs, and JEFTs.

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hBN

2025-07-09
10:40 - 11:55
hBN

PC-Wed-1 - The carbon dimer in boron nitride

2. Physics and characterization

Guillaume CASSABOIS[1]
[1] Laboratoire Charles Coulomb, CNRS, Montpellier University, 34095 Montpellier, France

Abstract text: Hexagonal boron nitride (hBN) is a wide-band-gap semiconductor which differs from other nitrides because of its sp2-hybridized bonds forming honeycomb atomic planes weakly stacked through the van der Waals interaction [1]. The growth of high-quality crystals in 2004 has revealed that hBN is a promising material for light-emitting devices in the deep ultraviolet domain, as illustrated by the demonstration of lasing at 215 nm by accelerated electron excitation [1], and also the operation of field emitter display-type devices in the deep ultraviolet [2]. The most common source of hBN corresponds to the so-called AA' stacking of atomic planes, where boron and nitrogen atoms alternate along the c axis. Other polytypes have different stacking sequences of the basal plane: Bernal boron nitride (AB)hBN with an AB stacking, rhombohedral boron nitride (rBN) with an ABC stacking, and also turbostratic boron nitride (tBN), which differs from the previous two by the existence of some translational and rotational disorder in the vertical stacking. In all these polytypes, there is an ubiquitous deep level emission with a sharp zero-phonon line at ~4 eV, the origin of which is highly debated.

I will discuss here our results unveiling the origin of the 4 eV-defect in boron nitride. We have combined isotope substitution and polytype control, with a systematic comparison between experiments and first-principles calculations. From isotopic purification of the host hBN matrix, a local vibrational mode of the defect is uncovered, and isotope-selective carbon doping proves that this mode belongs to a carbon-based center. Then, by varying the stacking sequence of the host hBN matrix, we unveil different optical responses to hydrostatic pressure for the non-equivalent configurations of this ultraviolet color center. We conclude that this defect is a carbon dimer in the honeycomb lattice of boron nitride. Recent results in high-quality rBN will be further discussed, completing the picture of the optical response of the carbon dimer in boron nitride.

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PC-Wed-2 - Cathodoluminescence spectroscopy of layered-structure BN thin films grown by metalorganic vapor phase epitaxy using tris(dimethylamino)borane

2. Physics and characterization

Kohei Shima[1]
Haruto Tsujitani[1], Shigefusa Chichibu[1]
[1] Inst. Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai 980-8577, Japan

Abstract text: Hexagonal (h)BN, a two-dimensional material with sp^2 bonding (stacking order AA'), is an indirect bandgap semiconductor [1] and exhibits high-efficiency excitonic emission around 215 nm, corresponding to its bandgap of approximately 6 eV at room temperature [2]. This makes it a promising material for deep ultraviolet (DUV) light emission. Another polytype of sp^2-BN, rhombohedral (r)BN (stacking order ABC) [3], also exhibits emissions around 215 nm. Vapor-phase growth methods have successfully produced hBN and rBN segments, showing potential for large-area scalability. However, BN films exhibiting sharp excitonic emissions have only been achieved using the halide vapor-phase growth method (BCl_3/ NH_3 system) by the Shizuoka Univ. group [4]. This study reports the growth and the DUV emission properties of sp^2-BN films by MOVPE using tris(dimethylamino)borane (TDMAB) and NH_3.

BN films were grown on *c*-plane Al_2O_3 substrates by MOVPE using TDMAB and NH_3. Growth temperatures ranged from 1300 to 1500 ºC. X-ray diffraction patterns consisted of the α-Al_2O_3 substrate, wurtzite AlN layers via nitridation of Al_2O_3, and sp^2-BN. Low-temperature CL measurements revealed a dominant 4 eV emission band, likely arising from carbon-related defects [5]. A 5.5 eV band, attributed to stacking disorder in sp^2-BN [6], was also prominent, similar to BN films grown using other metalorganic precursors [7]. Faint peaks, corresponding to the phonon replicas of indirect exciton recombination in hBN or rBN (5.7–5.9 eV), [1] were also detected. This is the first report on the DUV emission characteristics of sp^2-BN films grown using TDMAB/NH_3. Compared to the BCl_3/NH_3 system, the TDMAB/NH_3 system offered approximately twice higher CL intensity on average in the photon energy range of 5.2 to 6.0 eV at 300 K, likely due to reduced nonradiative recombination centers.

This work was supported in part by JSPS KAKENHI (20K20993, 23K22786, 23K17757), Japan. The authors thank Mr. T. Kasuya and Mr. S. Takaya of Tohoku Univ. for their help in modifying the MOVPE apparatus.

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PC-Wed-3* - Searching for Point Defects in Cubic Boron Nitride

2. Physics and characterization

William Stenlund[1]
Joel Davidsson[1], Viktor Ivády[2], Rickard Armiento[1], Igor Abrikosov[1]
[1] Department of Physics, Chemistry and Biology, Linköping University, Linköping, Sweden
[2] Department of Physics of Complex Systems, Eötvös Loránd University, Budapest, Hungary

Abstract text: Cubic boron nitride (c-BN) is a wide-bandgap semiconductor with potential applications in both power electronics and quantum technologies. Point defects have potential applications for single photon emitters and quantum sensors. However, a handful of defects have been identified, and several zero-phonon lines (ZPLs) have been measured in experiments but have not yet been attributed to any specific defect configuration [1]. Recent studies have also suggested point defects with emission in the telecom wavelength [2]. To systematically probe the combinatorially complex chemical space of defects, we generate large-scale point-defect data for c-BN. We apply density functional theory in a high-throughput manner using ADAQ [3] to broadly screen for point-defect complexes containing s- or p-elements. More than 8000 defects have been calculated in different charge and spin states, and their properties are stored in a database, which will be published [4]. In this presentation, we explore this database, focusing on properties such as formation energy, ZPL, and transition dipole moment.

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PC-Wed-4 - Cathodoluminescence studies of layered-structure BN epilayers grown by chemical vapor deposition using carbon-free molecules

2. Physics and characterization

Shigefusa CHICHIBU[1]
Takumi Kasuya[1], Haruto Tsujitani[1], Kazuhiko Hara[2], Kohei Shima[1]
[1] Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan
[2] Research Institute of Electronics, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu, Shizuoka 432-8011, Japan

Abstract text: (Synopsis) The near-band-edge (NBE) cathodoluminescence (CL) peaks in sp^2-bonded BN epilayers grown by chemical vapor deposition (CVD) on a sapphire substrate using carbon-free molecules (BCl_3 and NH_3) will be presented to assign the origins and extend the knowledge for the growth. The NBE excitonic peaks principally originate from rhombohedral (r) BN segments with small amount of Bernal (b) BN, and relative bBN peak intensity decreases with increasing NH_3/BCl_3 (V/III) ratio.
(Contents) Layered (sp^2) hexagonal (h) BN with AA'-stacking is attracting attention because it has an ultrawide bandgap (6 eV) and exhibits reasonably intense deep-ultraviolet emissions [1] in spite of *indirect* excitons (iX) [2]. Recently, formation and properties of Bernal (b) BN with AB stacking [3] and rhombohedral (r) BN with ABC stacking [4] have been reported and the research scope was greatly expanded. We also have detected [5] a direct exciton (dX) emission at 6.035 eV from bBN inclusions in the BN films [5,6] grown by low-pressure (LP) CVD using carbon-free molecules. In this presentation, structural properties and CL spectra of the BN films grown using a cold-wall reactor [6] with limited C sources will be shown to assign the peak origins and extend the knowledge for the film growth.
Approximately 1-m-thick BN films grown on a (0001) Al_2O_3 at 1300 for 60 min by LP-CVD with various V/III ratios (1250 to 3000) and different source supply timings and a *Reference* BN film grown at 1400 for V/III=1000 using a hot-wall reactor [5] were compared. Low-temperature CL spectra of all BN epilayers exhibited excitonic fine structures between 5.7 and 6.1 eV. Judging from the peak energies and intensity ratios, all films are assigned to comprise predominant rBN segments and bBN inclusions. Triangular morphologies of the films support this assignment. Relative bBN peak intensity decreases with increasing NH_3/BCl_3 (V/III) ratio. Carrier dynamics of iXs/dX in the rBN/bBN films will be presented on site.
The authors thank S. Takaya and support by JSPS KAKENHI (18K04231, 20K20993, 23K17757, 23K22786), Japan.
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AlN - wafers and homoepitaxy

2025-07-10
08:30 - 10:00
AlN - wafers and homoepitaxy

GR-Thu-1 - High-speed HVPE growth of AlN homoepitaxial layers for AlN wafer fabrication

1. Growth

Yoshinao Kumagai[1]
[1] Department of Applied Chemistry, Tokyo University of Agriculture and Technology, Tokyo, Japan

Abstract text: It is essential to establish a mass-production technology for high-quality AlN single-crystal substrates for use in fabricating deep-UV light-emitting devices and high-power electronic devices.

The research group of the presenting author has been conducting research on the preparation of freestanding AlN substrates from thick homoepitaxial layers grown by hydride vapor phase epitaxy (HVPE) on AlN (0001) substrates prepared by physical vapor transport (PVT). It has already been demonstrated that homoepitaxial growth can be achieved at a rate exceeding 150 μm/h at 1450 °C without deterioration of crystalline quality by the HVPE using gaseous $AlCl_3$ generated by reacting solid Al metal with HCl gas in the source zone of the reactor (hereafter referred to as Al-HVPE) [1]. Based on the results obtained, mass production of freestanding AlN substrates with low dislocation densities (10^3 – 10^4 cm^{-2}) showing high deep-UV transparency due to low impurity concentration has become possible [2].

On the other hand, with the aim of eliminating the operational complexities of the Al-HVPE described above, we have recently developed an HVPE system in which a vaporizer filled with high-purity solid $AlCl_3$ is connected to the reactor, and the vaporizer is heated to supply gaseous $AlCl_3$ (hereafter referred to as $AlCl_3$-HVPE). Because $AlCl_3$ has a low sublimation temperature (approximately 181 °C), high-speed homoepitaxial growth similar to that achieved by the Al-HVPE can be achieved at vaporizer temperatures of about 150 °C.

The work using the Al-HVPE system was done in collaboration with Tokuyama Corporation and also with the support by Innovative Science and Technology Initiative for Security (No. JPJ004596), Acquisition, Technology & Logistics Agency (ATLA), Japan. The work using $AlCl_3$-HVPE system was done in collaboration with Stanley Electric Co., Ltd.

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GR-Thu-2 - Compensation control in Si doped AlN grown on single crystal AlN substrate

1. Growth

Pramod Reddy[1]
Pegah Bagheri[2], Cristyan Quiñones-Garcia[2], Chao-I Liu[2], Dolar Khachariya[1], Ronny Kirste[1], Will Mecouch[1], Seiji Mita[1], Ramon Collazo[2], Zlatko Sitar[2]
[1] Adroit Materials
[2] North Carolina State University

Abstract text: AlN is an attractive material for fabricating short wavelength optoelectronic and high power devices. AlN, due to its wide bandgap of ~6.1 eV, offers high breakdown fields (15 $MVcm^{-1}$) and consequently a Baliga's figure of merit (BFOM) orders of magnitude larger than even wide bandgap materials such as GaN and SiC allowing for a more compact and higher voltage power electronics. However, BFOM assumes shallow dopants and no compensation. N-type AlN has been primarily achieved by doping with silicon during epitaxial growth. However, the conductivity exhibits a "knee behavior" with a sharp reduction beyond a low and high doping thresholds thus presenting doping limits. Further, Si transitions to a deep state resulting in a high activation energy and low carrier concentrations. Consequently, the BFOM is much lower than predicted. Hence a major "point defect problem" exists in AlN.

In this work, we demonstrate a systematic chemical potential control (CPC) based point defect mitigation where we relate the growth environment variables to the defect formation energy by determining and controlling the defect constituents' chemical potentials (μ) and thus choose the growth environment necessary for minimal compensating point defect incorporation or generation. At lower Si concentrations, we find contributions from nitrogen substitutional defects such as C_N and O_N reduces the carrier concentrations. Thus, by increasing $\mu_{N,}$ their energy of formation can be increased and thus compensation reduced. We demonstrate improved low doping limits with carrier mobility >300 cm^2/Vs. At higher Si concentrations, contributions of complexes of Si with Al vacancies increases resistivity. Thus, by growing in a more Al rich environment at low NH_3 partial pressures, peak conductivity is improved. Further, by calculating the chemical potentials as a function of growth temperature, we find that μ_{Al} remains nearly invariant. Consequently, the defect formation energy remains constant, and the incorporation of vacancies should decrease with decrease in growth temperature. Accordingly, by decreasing the growth temperatures from 1350 °C to 1100 °C, the carrier concentration increased in agreement with theory. Expectedly, the mobility also increased as the carrier concentration increased clearly indicating reduction in compensation.

GR-Thu-3* - Analyzing the influence of hydrogen on AlGaN layer growth by Halide Vapor Phase Epitaxy

1. Growth

Arianna Jaroszynska[1]
Karol Pozyczka[1], Petro Sadovyi[1], Robert Kucharski[1], Karolina Grabianska[1], Pawel Kempisty[1], Marek Zak[1], Michal Bockowski[1], Tomasz Sochacki[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: Aluminum Gallium Nitride ($Al_xGa_{1-x}N$) is a ternary alloy used in gallium nitride (GaN)-based High Electron Mobility Transistor (HEMT) designs [1]. These AlGaN/GaN structures are essential for high-power, high-frequency electronics due to their rapid switching capabilities and high breakdown voltages. However, their performance is often constrained by the use of foreign substrates such as sapphire. Native or near-native substrates could greatly enhance device performance by mitigating strain-related issues. Halide vapor phase epitaxy (HVPE) constitutes a favored method for growing both doped and undoped GaN crystals [2]. Recent studies confirm that $Al_xGa_{1-x}N$ alloys can also be grown by HVPE method [3].

In this work, we present comprehensive experimental results supported by simulations on the optimized growth of $Al_xGa_{1-x}N$ layers on GaN grown by the ammonothermal method [4]. We show findings from $Al_xGa_{1-x}N$ growth experiments using two metal chloride precursors HCl and Cl_2. Furthermore, we analyze the impact of H_2 on the crystallization process through both, thermodynamic calculations and experimental data. The analysis includes the comparison of final layer thickness on the crystal surface with the simulated distribution of reactants in the reactor. Our simulations support the experimental outcomes by providing insights into supersaturation calculations based on H_2 admixture in the carrier gas, the effectiveness of HCl vs. Cl_2 as active gases on the reactant synthesis ratio, and the modeling of gas dynamics during the growth phase. Our experimental approach has successfully produced a 60 µm-thick layer containing approximately 10 at.% Al content in a single growth run. This process not only shows promise for the growth of even thicker $Al_xGa_{1-x}N$ layers on Am-GaN but also for the fabrication of free-standing $Al_xGa_{1-x}N$ substrates. We will present and discuss the detailed experimental results, including morphology, Al content analysis, and structural quality by XRD, which are all underpinned by the simulations.

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GR-Thu-4* - Pulsed MOCVD Doping and Compensation in Si-AlN over bulk AlN Substrates

1. Growth

Tariq Jamil[1]
Abdullah Al Mamun Mazumder[1], Mafruda Rahman[1], Muhammad Ali[1], Jingyu Lin[2], Hongxing Jiang[2], Grigory Simin[1], Asif Khan[1]
[1] Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208, USA
[2] Department of Electrical & Computer Engineering, Texas Tech University, TX 79409, USA

Abstract text: AlN is an excellent choice for high-temperature/voltage/power electronic and optoelectronic devices due to its high breakdown field ~15 MV/cm, thermal conductivity ~ 300 W/m-K, and Baliga Figure of Merit (BFOM). However, the high ionization-energy of dopants, and the formation of self-compensating defects severely limit the doping control and hence the progress in AlN power and optical devices.

In this work we present a systematic comparative study of Si-doping of AlN epilayers over bulk AlN substrates using conventional, and Pulsed MOCVD (P-MOCVD) growth. The first set samples studied consisted of 250 nm undoped AlN buffer layer (conventional MOCVD) followed by 200 nm Si-doped layer grown with conventional and PMOCVD at 1150 ºC and 40 torr. SIMS data was used to confirm the presence of nearly identical Si-dopant density (doping ~ 2×10^{19} cm^{-3}) in them. TLM data from the two samples showed the conductivity of the PMOCVD sample to be ~ 15 times higher. For both samples, the room-temperature pulsed excimer laser (l~193 nm) photoluminescence (PL) showed a strong band edge signal (5.95 eV) and a deep level peak at 3.2 eV. The deep level peak, which increases with the Si-doping concentration, has been assigned to Al-vacancy complexes resulting from silicon doping. Since both samples had identical growth temperatures, the increased conductivity in the PMOCVD sample cannot be from a reduction of the compensating defects which are a strong function of the growth temperature and Si concentration.

To further study compensation and its role in sample conductivity, another set of PMOCVD samples were then grown. These consisted of sample (A-C) growth temperature 1150 ºC, 1075 ºC, 1075 ºC and the Si-dopant concentration 2×10^{19} cm^{-3}, 2×10^{19} cm^{-3} and 1×10^{19} cm^{-3}, respectively. The n-TLM measurements show the conductivity of both low temperatures grown samples to be higher than those grown at the high temperature. Conductivity further increased by reducing the Si-dopant density by a factor of 2. This confirms the role of compensating defects in reducing the conductivity of Si-doped AlN. From the PL data we see that lower growth temperatures and lower Si significantly reduced the defect related peak emission peak at 3.2 eV. In addition to doping and compensation, initial results on the use of these layers for lateral conduction Schottky barriers will also be presented.

GR-Thu-5 - Coherently grown AlN/GaN HEMT heterostructures on AlN buffer on SiC substrate with a mobility exceeding 600 cm2/V.s

1. Growth

Ravikiran Lingaparthi[1]
Tian Long Alex Seah[2], Rizwana Khanum[3], Dharmarasu Nethji[1], Radhakrishnan K[4]
[1] Temasek Laboratories, Nanyang Technological University, Singapore.
[2] Temasek Laboratories, Nanyang Technological University, Singapore
[3] ERIAN, Nanyang Technological University, Singapore.
[4] Centre for Micro/Nano-electronics (CMNE), Temasek Laboratories, ERIAN, Nanyang Technological University, Singapore.

Abstract text: AlN/GaN/AlN high electron mobility transistor (HEMT) heterostructures are advantageous for developing high-frequency and high-power devices, owing to their thin barrier layer and high polarization-induced two-dimensional electron gas, respectively. Recently, the coherent growth of AlN/GaN/AlN HEMT heterostructures has been demonstrated on AlN substrates with Si δ-doping at the GaN channel/AlN buffer, resulting in improved mobility by reducing dislocations in the GaN channel and lowering the electric filed. [1] Si δ-doping also keeps the Fermi level away from the deep trap states located above the valence band [2], effectively minimizing dispersion.

In coherently grown AlN/GaN/AlN on AlN substrate, the GaN channel is 30 nm thick. However, achieving similar coherent growth of AlN/GaN on AlN buffer on SiC substrate with Si δ-doping presents several challenges such as enhanced GaN channel relaxation due to high dislocation density in AlN buffer and due to additional tensile stress generated because of heavy Si doping.

To mitigate stress at the GaN channel/AlN interface for enhanced structural reliability, this study explores the coherent growth of AlN/GaN HEMT heterostructures on a 450 nm AlN buffer on SiC substrate, incorporating AlGaN stress-mitigating layers (SMLs). As a reference, AlN barrier was grown on 60 nm thick and relaxed GaN channel. Hall measurements revealed a Hall mobility (μ_H) of 581 $cm^2/V{\cdot}s$, a 2DEG concentration (n_s) of 2.9×10^{13} cm^{-2}, and a sheet resistance (R_{sh}) of 359 Ω/sq. Reduction of GaN chnnel thickness to 9 nm, but with Si δ-doping, also resulted in high relaxation of GaN channel. Relaxation occurs in these heterostructures through misfit formation. However, with thicker AlGaN SMLs introduced between AlN and GaN, heterostructures relaxed through cracking. By optimizing AlGaN SMLs and with Si δ-doping, coherently grown AlN/GaN HEMT heterostructures were achieved on AlN buffer on SiC substrate. Hall measurements resulted in μ_H, n_s, and R_{sh} of 626 $cm^2/V{\cdot}s$, 2.4×10^{13} cm^{-2}, 413 Ω/sq·, respectively. These values represent the highest reported for a coherently grown AlN/GaN/ (AlN) HEMT heterostructure on a SiC substrate.

[1]Yu-Hsin Chen et al., Appl. Phys. Lett. 125, 142110(2024). [2] R. Lingaparthi et al., Appl. Phys. Lett. 122, 172103(2023).

This research is supported by Grant Call-10264 A*STAR IAF– IAF-PP RIE2025: M22L3a0112.

Visible and THz lasers

2025-07-10
08:30 - 10:00
Visible and THz lasers

OD-Thu-1 - Embedded grating DFB laser diodes and amplifiers

3. Optical devices

Ryan Anderson[1]
Justin Melkun[2], Fu-Chen Hsiao[2], Collin Roy[2], Jonathan Wierer[2], Fred Kish[2], Seunggeun Lee[1], Josh D. Brown[1], Ian Mann[1], Emily Trageser[3], Amy Zhang[3], Steven P. DenBaars[3], Jim Haden[1]
[1] BluGlass Ltd, 74 Asquith St Silverwater, NSW, 2128, Australia
[2] Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27606, USA
[3] Materials Department, University of California, Santa Barbara, California 93107, USA

Abstract text: Nitride-based distributed feedback (DFB) laser diodes have high spectral purity, stability, and robust emission ideal for applications in communication, optical clocks, quantum sensing, quantum computing, and integration onto compact photonic circuits. However, improvements are needed in linewidth, wavelength control, and output power to fully enable their use in precision applications.

Developments of DFB lasers and related technology will be shared. Near single-frequency stability and optical intensity distribution across the laser cavity are investigated with respect to design parameters. Devices spanning 408 nm – 470 nm demonstrate improvements in spectral performance, with side-mode suppression ratios (SMSR) up to 40 dB and spectral full-width at half-maximum (FWHM) below 3 pm and limited by the spectrometer.

We further report on pairing of DFB lasers with semiconductor optical amplifiers (SOAs) targeting high-power, narrow-linewidth sources. Light-current-voltage characteristics under varying SOA drive conditions and far-field beam profiles are presented, demonstrating beam quality suitable for master oscillator power amplifier (MOPA) configurations. Multi-section lasers show fine wavelength tunability over 100 pm with high SMSR. These results represent a step toward scalable, high-performance GaN photonic chips for next-generation precision optical systems.

OD-Thu-2* - Low-Threshold and Single-Mode DFB Lasers through Feedback Matching Strategy

3. Optical devices

Feifan Xu[1]
Jushi liu[2], Zhe Zhuang[2], Tao Tao[1], Rong Zhang[3], Bin Liu[1]
[1] School of Electronic Science and Engineering, Nanjing University, Nanjing, China.
[2] School of Integrated Circuits, Nanjing University, Suzhou, China
[3] Xiamen University, Xiamen, China

Abstract text: Single-mode lasers are extensively used in high-resolution spectroscopy, optical communications, environmental sensing, and medical diagnostics owing to their narrow linewidth and excellent spectral purity. Among various single-mode laser configurations, distributed feedback (DFB) lasers stand out for their compact design and inherent ability to achieve stable single-mode emission without external filters or cavities. However, short-wavelength DFB lasers have long faced challenges stemming from difficult material growth and intricate fabrication processes needed to produce high-quality gratings, often resulting in elevated threshold currents and reduced device efficiency.

In this study, we propose a weak feedback matching strategy to lower the threshold current of GaN-based DFB lasers while maintaining robust single-mode performance. Our approach focuses on optimizing the feedback contributions from both the distributed grating and the native end-facet reflections, enabling single-mode lasing at currents comparable to those of conventional Fabry-Perot (FP) lasers. We implement this strategy by using focused ion beam (FIB) technology to inscribe a grating in the P-side cladding layer, with a period of 895 nm and a 30% duty cycle. These parameters are carefully selected to precisely control the coupling between the grating and the dominant optical mode. By tuning the coupling constant, we successfully minimize the threshold current while preserving high-quality single-mode emission. The optimized DFB laser demonstrates a single-mode threshold current of just 25 mA, closely matching that of an equivalent FP laser. In addition, the side-mode suppression ratio (SMSR) exceeds 30 dB, and the linewidth narrows to approximately 50 pm. These results highlight the potential of the weak feedback matching strategy to tackle longstanding challenges in short-wavelength DFB lasers, paving the way for compact, low-power devices with superior spectral characteristics.

OD-Thu-3 - Narrow-linewidth GaN-based laser diodes with high-order gratings

3. Optical devices

Meixin FENG[1]
Yongjun TANG[1], Qian SUN[1], Hui YANG[1]
[1] Suzhou Institute of Nano Tech and Nano Bionics, Chinese Academy of Science, Suzhou,China

Abstract text: III-nitride semiconductors have a bright prospect in laser diode (LDs) with a wide emission wavelength raging from ultraviolet to infrared and a high luminous efficiency. However, all commercial GaN-based LDs are operated in multiple longitudinal modes, which cannot meet the demands in narrow linewidth, highly coherent and accurate wavelength tuning for the emerging applications in the underwater LiDAR, holographic storage, atom cooling and atom clocks. Furthermore, using Si substrate to grown GaN-based LDs can greatly slash down the cost due to a larger wafer size and lower material cost of Si substrates as compared with free-standing GaN substrates, and the potential adoption of large-scale, low-cost manufacturing foundries. Narrow-linewidth GaN-based LDs grown on Si may also serve as a potential on-chip light source for Si photonics with III-nitride waveguide. Therefore, it's very attractive to develop narrow-linewidth GaN-based LDs directly grown on Si.

In this study, high-order sidewall gratings were fabricated along the side of ridge, and tetramethyl ammonium hydroxide (TMAH) post-treatment was conducted to remove etching damage and make the sidewall smooth and steep. As a result, we have successfully demonstrated GaN-based distributed feedback LDs grown on Si. Further studies revealed that the increase of optical loss and decrease of injection efficiency resulting from the fabrication of the gratings were responsible for poor device performance.

To overcome these issues, we designed and fabricated the electrically pumped narrow-linewidth GaN-on-Si LDs with slot gratings. Only a few rationally designed slot gratings were introduced into the ridge of conventional Fabry–Pérot (F–P) cavity LDs to narrow the linewidth. As a result, the threshold current was only increased by 11% after the slot fabrication, in stark contrast to more than two times reported in the literatures, and the lasing spectrum was also improved with a side-mode suppression ratio of 13 dB and a full width at half maximum of 25 pm. Afterwards, we reported a novel fabrication technology to not only reduce the remaining p-type layer in the sidewall gratings, but also realize close-coupled sidewall gratings. Finally, GaN-on-Si DFB LDs with an emission wavelength of 414 nm, FWHM of 22 pm, and SMSR of 19.1 dB were realized.

OD-Thu-4* - Distributed-Feedback Laser Diodes Using Absorptive Chromium Gratings

3. Optical devices

Julian Kassmann[1]
Eva Raffalt[2], Folke Dencker[2], Rany Miranti-Augustin[1], Florian Meierhofer[1], Jana Hartmann[1], Alexander Fernandez Scarioni[3], Thomas Weimann[3], Marc Wurz[2], Andreas Waag[1]
[1] Nitride Technology Center, Institute of Semiconductor Technology, TU Braunschweig, Braunschweig, Germany
[2] Nitride Technology Center, Institute of Micro Production Technology, Leibniz University Hannover, Garbsen, Germany
[3] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Abstract text: As quantum technologies further mature, the demand for new light sources increases in order to improve both efficiency and scalability. Light sources with blue emission and extremely small linewidths are required, elevating gallium nitride (GaN)-based laser diodes to prime candidates. However, conventional Fabry-Perot laser diodes are unable to achieve the required linewidths due to the presence of numerous longitudinal modes. In contrast, distributed-feedback (DFB) laser diodes incorporate a grating structure that ensures the emission of a single wavelength.

The application of a metallic Bragg grating structure for conventional III-V DFB laser diodes has been well-documented for over 25 years. While these laser diodes typically emit in the near- to mid-infrared spectrum, there are no reports of GaN-based DFB laser diodes with a lateral metallic grating. This type of grating structure remains largely independent from the actual semiconductor material, as the distributed-feedback originates from the alternation between the metal strips and passivation material.

In our contribution, we present an electrically-pumped, GaN-based, DFB laser diode with an integrated metal grating for selective absorption of the longitudinal modes alongside the cavity. The grating contains of a vast number of chromium stripes that are oriented perpendicular to the lasing ridge, processed using electron beam lithography and a conventional lift-off step. The design parameter of the grating are matched for a 455 nm emission wavelength. We operate the fabricated laser diodes under pulsed electric current with a pulse width of 10 µs at a frequency of 1 kHz, and investigate their light output-current-voltage (LIV) characteristics and high resolution emission spectra. Notwithstanding the relatively high threshold currents ($I_{th} \approx 200$ mA), the devices demonstrate emission spectra with comparatively narrow linewidths (FWHM ≈ 76 pm), a high side-mode suppression ratio (SMSR ≈ 23 dB), and a weak temperature-induced peak wavelength redshift of 13 pm/K over the 10 to 28 °C temperature range. These observations provide substantial evidence in support of DFB lasing for our GaN-based laser diodes.

OD-Thu-5* - Above Room Temperature Optical Gain in 3-15 THz Range GaN/AlGaN Quantum-Cascade Laser obtained by NEGF Analysis

3. Optical devices

Koki Yabe[1]
Airu Takahashi[1], Akira Kaneko[1], Li Wang[1], Ke Wang[1], Sachie Fujikawa[2], Krishan Kumar[1], Shashank Mishra[1], Thomas Grange[3], Stefan Birner[3], Hiroyuki Yaguchi[2], Hideki Hirayama[1]
[1] RIKEN
[2] Saitama University
[3] nextnano GmbH

Abstract text: Terahertz quantum-cascade lasers (THz-QCLs) have attracted attention as excellent THz light sources due to their compact size, high output power, narrow linewidth, long lifetime, and high durability, and are expected to be used in a variety of applications. However, it is difficult to realize over 300K operation by GaAs-based QCL, and their operating frequency range is limited to 1.2-5.4 THz. This is because the electron-LO phonon energy (E_{LO}) of GaAs is 36 meV, which is close to the thermal energy at room temperature, and there is an heavy optical absorption band at 5-12 THz. In contrast, GaN-based semiconductors have a large E_{LO} of 92 meV, GaN-based QCL is predicted to operate in the 1.5-15.5 THz range, including the unexplored 5-12 THz range, and also it is suitable for over 300K operation. In this study, we optimized the structure of a GaN/AlGaN-based THz-QCL and analyzed the optical gain above room temperature in the 3 to 15 THz region.

Assuming a GaN/$Al_{0.13}Ga_{0.87}N$ 3-quantum well (QW), 4-level structure (IL; injection level, ULL; upper lasing level, LLL; lower lasing level, EXT; extraction level), we analyzed the optical gain using the non-equilibrium Green's function (NEGF) method to obtain a strict solution. We investigated the transition mechanism in various frequency regions based on 10 THz QCL. It was found that the maximum temperature at which population inversion occurs in a 10 THz QCL is about 450 K, and the limit temperature at which an optical gain of over 30 cm^{-1} is about 380 K. We found that the lasing frequency can be tuned from 2 to 15 THz by changing the thickness of the two layers, i.e., the injection well and the emission barrier. It was found that the optical gain is limited by the effects of LO phonon scattering at high frequencies and by broadening of the oscillation levels at low frequencies, and the room temperature operation range is approximately 2 to 14.7 THz. It was also revealed that at around 3 THz region, optical gain occurs not only between ULL and LLL but also between LLL and EXT, and the gain is significantly improved at the temperature higher than 300K. We also found that doping the injection layer significantly improves the optical gain. In conclusion, we have shown through our analysis that GaN-based QCLs are capable of room temperature oscillation in a wide range from 2 to 14.7 THz.

Novel Electronic Devices 2 (Materials)

2025-07-10
08:30 - 10:00
Novel Electronic Devices 2 (Materials)

ED-Thu-A1 - Ferroelectricity for a New Perspective on III-N Semiconductors

4. Electronic devices

Georg Schönweger[1]
Niklas Wolff[2], Tom-Niklas Kreutzer[3], Md Redwanul Islam[2], Adrian Petraru[4], Hermann Kohlstedt[4], Fabian Lofink[1], Lorenz Kienle[2], **Simon Fichtner**[1]
[1] Department of Materials Science, Kiel University, Kiel, Germany and Fraunhofer ISIT, Itzehoe, Germany
[2] Department of Materials Science, Kiel University, Kiel, Germany
[3] Fraunhofer ISIT, Itzehoe, Germany
[4] Department of Electrical Engineering, Kiel University, Kiel, Germany

Abstract text: The spontaneous polarization P_{spont} is one of the key properties of the wurtzite III-N semiconductors AlN, GaN and InN. The emergence of ferroelectricity in these compounds, i.e. the ability to change direction and net-magnitude of P_{spont} through electric fields, is poised to lead to new paradigms in the design and usage of III-N devices: 1.) Ferroelectric III-Ns can enable seamless integration of memory functionality and reconfigurable material coefficient tensors (piezoelectric coefficients, nonlinear optical susceptibility) in III-N technology. 2.) Ferroelectricity can create and annihilate previously inaccessible polarization patterns and functional polar domain walls in the bulk as well as on the interfaces of III-N heterostructures. 3.) Ferroelectric switching allows direct experimental determination of P_{spont} (magnitude and sign), thereby confirming the necessity for reconsidering P_{spont} in line with more recent theoretical prediction (P_{spont} > 1 C/m² for metal-polarity).[1-3]

In addition to highlighting how ferroelectricity can thus shape a new perspective on III-N semiconductors, this contribution will discuss recent progress towards understanding and harnessing the implications of ferroelectric III-Ns based on two examples: First, electric field induced polarization discontinuities are apparently able to concentrate massive bound charge (~ 200 µC/cm²) in atomically sharp interfaces. This bound charge in turn induces conductive sheets (domain walls) that can e.g. directly serve for the purpose of resistive memories. On/off ratios and operating voltages attractive for in-memory computing are demonstrated.

Second, inverted piezoelectric tensors allow for multilayers with a piezoelectric output that rivals that of state-of-the-art lead-containing perovskites – at significantly better linearity, durability, as well as reduced power demand. This development has the potential to open yet another significant application field for III-N semiconductors: that of high-power actuators for e.g. acoustic and optical microsystems.

[1] S. Fichtner *et al.*, J. Appl. Phys. 125 (2019)

[2] S. Fichtner *et al.*, Appl. Phys. Lett. 125 (2024)

[3] Z. Mi *et al*., Appl. Phys. Lett. 124 (2024)

ED-Thu-A2 - Piezoelectric (Al,Sc)N thin films grown by molecular-beam-epitaxy as a platform for surface-acoustic-wave generation

4. Electronic devices

Mingyun Yuan[1]
Duc V. Dinh[1], Denis Alikin[2], Alexander Tselev[2], Soumen Mandal[3], Oliver A. Williams[3], Oliver Brandt[1], Paulo V. Santos[1]
[1] Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., 10117 Berlin, Germany
[2] Department of Physics and CICECO-Aveiro Institute of Materials, University of Aveiro 3810-193 Aveiro, Portugal
[3] School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, UK

Abstract text: $Al_{1-x}Sc_xN$ is attracting increasing attention due to the enhanced piezoelectricity as a result of the Sc incorporation [1], which leads to higher electromechanical coupling efficiency and wider bandwidths for surface-acoustic-wave (SAW) devices, a key element in telecommunication and sensing. Whereas sputtering provides an efficient way to synthesize such thin films, plasma-assisted molecular beam epitaxy (PAMBE) can potentially yield films with better crystal quality. Here, we have developed a universal process to synthesize (Al,Sc)N thin films on a series of substrates including Si [2], SiC, and diamond [3], gearing towards surface-acoustic-wave (SAW) applications. Studies of the piezoelectric properties of the wurtzite films using piezoresponse-force microscopy (PFM) indicates a microscopic polarization switching by the electrically biased probe for a high Sc-concentration film (x~0.25). The result contrasts with the uniform behavior observed in ferroelectric measurement [4]. We then fabricate SAW transducers and investigate SAW generation in the 2 to 8 GHz frequency range. We compare different substrates from the viewpoints of PAMBE growth and SAW excitation, respectively. While Si remains the most important substrate in semiconductor technology, SiC provides a close lattice match, and the extremely high sound velocity of diamond is optimal in supporting multiple higher SAW modes. We will present the study of SAW in both scattering-parameter measurement in the frequency domain as well as high-resolution scanning-probe of the spatial profile using atomic-force microscopy (AFM). Perspectives as well as challenges related to the material platform will be discussed.

[1] M. Akiyama et al., Appl. Phys. Lett. 95, 162107 (2009)

[2] D. V. Dinh et al., APL Materials, in press (2025)

[3] M. Yuan et al., J. Phys. D: Appl. Phys., 57, 495103 (2024)

[4] S. Fichtner et al., J. Appl. Phys, 125, 114103 (2019)

ED-Thu-A3 - Enhancement of 2DEG Density by Sputtering Regrowth of ScAlN on AlGaN/AlN/GaN Heterostructure

4. Electronic devices

Kouei Kubota[1]
Yusuke Wakamoto[1], Takahiko Kawahara[2], Shigeki Yoshida[2], Kozo Makiyama[2], Ken Nakata[2], Atsushi Kobayashi[3], **Takuya Maeda**[1]
[1] The University of Tokyo, Dept. of Electrical Engineering and Information Systems, Tokyo, Japan
[2] Sumitomo Electric Industries Ltd., Transmission Devices Laboratory, Yokohama, Japan
[3] Tokyo University of Science, Tokyo, Department of Materials Science and Technology, Japan

Abstract text: ScAlN exhibits unique properties such as strong polarization and ferroelectricity, which is attractive as barrier material of a GaN HEMT. We have reported on epitaxial growth of ScAlN thin films on GaN by a sputtering method [1-3]. In this study, we investigate the effect of a sputtering regrowth of a ScAlN thin film on a GaN HEMT structure. The transport properties of 2DEG in the heterostructures with and without the ScAlN layer were measured and discussed.

A ScAlN thin film was grown on a $Al_{0.22}Ga_{0.78}N$ (3 nm)/AlN (1 nm)/GaN heterostructure, which was beforehand grown by MOVPE on a semi-insulating 6H-SiC substrate, by a sputtering. The Sc composition and the thickness are 9% and 10 nm, confirmed by TEM. From the XRD reciprocal space mapping around 10-15 diffraction, the coherent growth of ScAlN on GaN was confirmed. The sample without the growth of a ScAlN thin film was also prepared as a control sample.

Temperature-dependent Hall effect measurements were carried out for the samples. For the control sample (w/o ScAlN), the sheet electron density and mobility are 3.8×10^{12} cm^{-2} and 1825 cm^2/Vs at room temperature, respectively. For the sample with ScAlN, the sheet electron density was 1.5×10^{13} cm^{-2}, which is approximately 4 times higher than the control sample. However, the mobility decreased to 1162 cm^2/Vs. For both the samples, the mobilities increased and saturated as temperature decreased. The theoretical mobilities were calculated based on the Matthiessen's rule considering the polar optical phonon (POP), acoustic deformation potential (ADP) and interface roughness (IR) scatterings. The POP and ADP scatterings mainly depend on the effective mass and the dielectric constant. The IR scattering strongly depends on the roughness parameters of and . and were obtained by fitting the calculations to the experimental data at cryogenic temperature. Using the reasonable values of Λ=2.1 nm and δ=2.1 Å (Λ/δ=10), the calculations showed good agreement with the experimental data, indicating that the mobility degradation can be explained by the enhanced IR scattering due to the high sheet electron density. These results are useful to understand the transport properties of sputtered ScAlN/MOVPE-AlGaN/AlN/GaN heterostructure.

[1] A. Kobayashi *et al*., *APEX* **17**, 011002 (2023). [2] T. Maeda *et al*., *APL* **125***,* 022103 (2024). [3] T. Okuda *et al*., *APL* **126**, 052105 (2025).

ED-Thu-A4 - Demonstration of ScAlN/GaN RF HEMTs on silicon substrate

4. Electronic devices

Yvon Cordier[1]
Seif El Whibi[2], Nagesh Bhat[2], Yassine Fouzi[2], Nicolas Defrance[2], Jean-Claude DeJaeger[2], Zahia Bougrioua[2], Florian Bartoli[1], Maxime Hugues[1], Marie Lesecq[2]
[1] Université Côte d'Azur, CNRS, CRHEA
[2] Univ. Lille, CNRS, Centrale Lille, Univ. Polytechnique Hauts-de-France, UMR 8520 – IEMN

Abstract text: ScAlN ensures a very high carrier density at the interface with GaN, which makes it possible a promising barrier layer for HEMTs in view of power switching and RF/mm-wave power amplifier applications. We have demonstrated the feasibility of the growth with ammonia source MBE (NH_3-MBE) of $Sc_xAl_{1-x}N$ barriers quasi-lattice matched with GaN (x~14%) [1]. The advantages of this technique in terms of alloy homogeneity, growth rate and alloy composition control have been demonstrated and more recently ScAlN/GaN HEMTs have been grown on silicon substrate, allowing the fabrication of functional transistors with 2 µm gate length [2]. However, the surface of ScAlN rapidly oxidizes and suffers a lack of stability during the device process. For this reason, in-situ grown cap layers such as GaN, AlN or SiN have to be envisaged. In this work, the heterostructure is grown on a 3-inch high-resistivity Si(111) substrate covered with a 1.3 µm GaN buffer on a 0.4µm stress mitigating AlN/AlGaN/AlN stack. A 7 nm ScAlN barrier is grown at 670°C with a Sc molar fraction x=15%. A thin 1.6 nm AlN exclusion layer is introduced between ScAlN and GaN to limit intermixing and alloy scattering. Finally, a 2 nm GaN cap layer is grown on top of the barrier. The device process involves e-beam lithography, Ti/Al/Ni/Au annealed ohmic contacts, ion implantation for isolation, Ni/Au T-gates and passivation with PECVD silicon nitride. The DC characteristics of the 75 nm gate transistor with source to drain distance of 1.5 µm exhibit a resistance R_{on}=2 ohm.mm and a maximum drain current density of 1.35 A/mm at V_{GS}=0V, linked with a maximum transconductance of 284 mS/mm. Furthermore, the device exhibits a current gain cutoff frequency (f_T) of 82 GHz and a maximum oscillation frequency (f_{MAX}) of 112 GHz, demonstrating the potential of ScAlN/GaN HEMTs grown by NH_3-MBE on low-cost silicon substrates for RF applications.

This work is partly supported by the French technology facility network RENATECH, the national radio frequency characterization network RFnet, the National Research Agency through the 'Investissements d'Avenir' program GaNeX (ANR-11-LABX-0014) and the project TWINS (ANR-23-CE51-0011) as well as ECSEL JU project GaN4AP under Grant Agreement No. 101007310.

[1] C. Elias et al, Appl. Phys. Lett. Materials 11, 031105 (2023).

[2] C. Elias et al, Phys. Status Solidi A, 2400963 (2025).

ED-Thu-A5* - Ferroelectric Modulation in (Sc)AlN RF Transistors via Superlattice Barrier Engineering Epitaxied by MBE

4. Electronic devices

Jiajia Yao[1]
Jiajia Yao[1], Guanlin Wu[1], Junshuai Xue[1], Jincheng Zhang[1], yue Hao[1]
[1] State Key Laboratory of Wide-Bandgap Semiconductor Devices and Integrated Technology, Faculty of Integrated Circuit, Xidian University, Xi'an 710071, People's Republic of China

Abstract text: Aluminum nitride (AlN), as an ultra-wide bandgap semiconductor material, has shown significant potential in power electronic devices, deep ultraviolet optoelectronic devices, and high-temperature sensors due to its strong spontaneous polarization, high breakdown field, and excellent chemical stability. Recent research has discovered that by introducing scandium (Sc) to form $Sc_xAl_{1-x}N$ alloys, the ferroelectric properties of the material can be effectively tuned, providing a novel candidate material for micro-electromechanical systems (MEMS), radio frequency filters, and high-frequency high-power electronic devices. In this study, we successfully fabricated the high electron mobility transistors (HEMTs) with superlattice barrier structure of (Sc)AlN/GaN heterojunction on an AlN on Sapphire template using plasma-assisted molecular beam epitaxy (PA-MBE). This heterostructure consists of a GaN channel and a composite barrier layer, where the barrier layer employs an innovative superlattice design: the top layer is a ScAlN ferroelectric layer, and the bottom layer is a periodic AlN/GaN interlayer structure (Figure 1a). Atomic-scale characterization reveals that the active region has clear interface, with atomically sharp interfaces between the ScAlN/GaN/AlN layers (Figure 1b).

The T-gate HEMT device based on this heterostructure (with L_G=200 nm, L_{GD}=2 μm, and L_{GS}=1 μm, Figure1c) exhibits excellent performance: DC characteristics achieved a high on/off ratio of $>10^6$, and a significant hysteresis window observed in the transfer characteristic curves (Figure 2a,b) confirms the ferroelectric modulation of the ScAlN. In terms of high-frequency performance, the device achieves an impressive cutoff frequency of f_T/f_{MAX}=32/70 GHz with a gate length of 200 nm (Figure 2c). This work, through the synergistic optimization of ferroelectric modulation and superlattice barrier engineering, combined with an all-epitaxial heterogeneous integration with (Sc)AlN/GaN on AlN substrates, provides an innovative solution for the development of the next generation of radio frequency electronic devices.

Thermal Management and Reliability

2025-07-10
08:30 - 10:00
Thermal Management and Reliability

ED-Thu-B1 - Thermal management efforts for GaN electronic devices

4. Electronic devices

Martin Kuball[1]
[1] University of Bristol

Abstract text: GaN electronic devices with their increasing power density require large efforts in engineering/physics innovations to extract waste heat more efficiently than presently possible, to keep device temperature within sensible temperature ranges. Thermal heat management solutions including integration of diamond with GaN, microfluidics and heat pipes will be discussed, also packaging innovations such as metal diamond composites. The latest approaches in the thermal analysis of materials and devices to aid development of these thermal management solutions will also be highlighted. This includes thermal analysis imaging technique such as Raman thermography, also latest developments in being able to image temperature in devices with less than 200-400nm spatial resolution, furthermore the ability to measure thermal conductivity in three dimensions. This will be discussed in the context of standard GaN HEMTs though also advanced device structures such as GaN SCLFETs.

ED-Thu-B2 - Improved High-Temperature/High-Voltage Reliability of p-GaN/AlGaN/GaN HEMTs Through Gate Hole Injection

4. Electronic devices

Manuel Fregolent[1]
Carlo De Santi[1], Mirco Boito[1], Michele Disarò[1], Eleonora Canato[2], Maria Eloisa Castagna[3], Cristina Miccoli[3], Giansalvo Pizzo[4], Isabella Rossetto[1], Lorenzo Cerati[2], Ferdinando Iucolano[3], Gaudenzio Meneghesso[1], Enrico Zanoni[1], Matteo Meneghini[1]
[1] Department of Information Engineering, University of Padova, Padova 35131, Italy
[2] STMicroelectronics, Agrate Brianza (MB), 20864, Italy
[3] STMicroelectronics, Catania (CT), 95121, Italy
[4] STMicroelectronics, Cornaredo (MI), 20007, Italy

Abstract text: GaN high electron mobility transistors with p-GaN gate emerged as excellent devices for power electronics. The reliability of such devices under positive gate stress is widely discussed in literature, with several papers [1] that reported a negative activation energy of the time-to-failure (TTF) with a significant deviation from the traditional E-model. In this work we propose an advanced model for the degradation based on stress, electroluminescence and dynamic data.

Devices stressed at different positive gate voltages and temperature show that: (a) TTF increases at high temperatures, with a negative activation energy (-0.31 eV); (b) the acceleration factor of TTF vs stress voltage decreases at high voltage levels, thus suggesting a mitigation of the degradation trend.

The degradation model was built by investigating the origin of gate leakage. Two processes were identified: (i) at moderate gate bias, electrons from the 2DEG are injected in the p-GaN through thermionic emission; (ii) at higher gate voltages, conduction is dominated by trap-assisted-tunneling of holes from the gate contact [2]. This suggest that degradation is due to electrons accelerated in the Schottky SCR, that undergo impact ionization [3]. At the same time, the holes are accumulated in the 2DHG at the p-GaN/AlGaN interface. This latter result was confirmed by spectrally-resolved electroluminescence measurements, that provide evidence for band-to-band recombination.

The link between hole injection and TTF was analyzed by considering the V_{TH} kinetics during constant voltage gate stress. We identified a significant negative shift of V_{TH} due to hole trapping in the AlGaN barrier [4], that was then correlated to the difference between the “ideal” TTF (according to the E model), obtained by linear interpolation of the log(TTF) data at low gate stress. Remarkably, the results present an excellent exponential correlation between the amount of injected/trapped holes and the reduction in the acceleration factor observed at high gate voltages. This result demonstrates that hole injection has a beneficial impact on time-to-failure.

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ED-Thu-B3* - Enhanced Heat Dissipation of p-GaN/AlGaN/GaN HFET with Boron Nitride Passivation

4. Electronic devices

Jun-Hyeok Yim[1]
Jin-Hyeok Pyo[1], Sang-Yeon Pak[1], Ho-Young Cha[1]
[1] Hong-Ik University, Seoul, Korea

Abstract text: Thermal management of power devices is a critical factor for ensuring both reliability and minimizing thermal degradation. As the device channel temperature rises, on-resistance increases due to enhanced carrier scattering, leading to reduced conversion efficiency. This thermal degradation issue becomes even more pronounced in high power density devices, such as GaN power devices, which exhibit high channel carrier density and high carrier mobility. While package-level thermal management solutions have been extensively explored, device-level approaches remain relatively under investigated. In this study, we developed a high thermal conductivity BN passivation process for GaN-on-Si power devices. To evaluate the effectiveness of BN passivation, an E-mode pGaN HFET was fabricated, involving selective pGaN etching, the first SiO_2 ILD deposition, Ti/Al/TiN ohmic contacts, TiN gate, and the second SiO_2 ILD deposition. A 50nm BN passivation film was sputtered under deposition conditions(RF power 100W, Ar plasma 10sccm/10mTorr, 3h). Due to its low deposition temperature, BN passivation process ensures no thermal budget constraints on GaN device processing. The amorphous BN film forms a good thermal interface due to atomic-scale roughness. Electrical characteristics were compared before and after BN passivation. With the BN passivation film, The maximum current density increased from 362 to 454mA/mm, while on-resistance decreased from 12.44 to 11.60Ωmm. No shift in threshold voltage was observed after BN passivation, indicating that the BN passivation process did not influence the gate modulation property. It is suggested that the BN passivation film enhanced heat dissipation at the surface, effectively lowering the channel temperature. The lower channel temperature contributed to higher current density and lower on-resistance. Temperature-dependent I-V characteristics were studied from room temperature to 150C. As the temperature increased from room temperature to 150C, the maximum current density decreased by 40% and the on-resistance increased by 90%. A conventional device without BN passivation exhibited greater degradation at elevated temperature. In conclusion, the BN passivation process demonstrates strong potential as an effective heat dissipation technique at the device surface, thereby improving the thermal performance and reliability of GaN power devices.

ED-Thu-B4* - High Power Load Pull Characterization of Scaled Gallium Nitride High Electron Mobility Transistors in D-band

4. Electronic devices

Weifeng Wu[1]
Lei Li[2], Juncheng Xiong[1], James C. M. Hwang[2], **Patrick Fay**[1]
[1] Department of Electrical Engineering, University of Notre Dame, Notre Dame, USA
[2] School of Electrical and Computer Engineering, Cornell University, Ithaca, USA

Abstract text: The demand for high-performance power devices at D-band (110–170 GHz) is rapidly growing, driven by emerging high-speed wireless communication applications. While GaN-based HEMTs have shown excellent power capabilities at mm-wave frequencies, its viability at D-band requires further exploration. In this work, scaled GaN HEMTs are characterized at D-band using active load-pull, providing key insights into their potential for D-band applications.

The measurement system comprises a Keysight N5245B vector network analyzer, a Vertigo vector modulator, two VDI WR6.5VNATxRxM-4HP frequency extenders, and FormFactor I170-S-GSG-50-BT probes. To ensure accurate power leveling and control, a first-tier two-port TRL waveguide calibration at the frequency extender output flanges plane was applied, followed by waveguide port power calibration and leveling using a VDI Erickson PM5B power meter, and then the final measurement plane was moved to on-wafer device measurement plane by a second-tier two-port TRL calibration. The system can supply up to 22.9 dBm of input power to the device under test at the probe tip reference plane at 140 GHz. The measured transistors were fabricated in HRL Laboratories' "T3" 40-nm GaN-on-SiC HEMT technology, provides nominal f_t's of 200 GHz and f_{max}'s of 400 GHz.

The devices exhibit a maximum drain current (I_d) of approximately 900 mA/mm at a gate voltage of 1 V, a threshold voltage of -0.08 V, and peak transconductance of 609 mS/mm. Load pull was performed for $|\Gamma_{load}|$ up to ~0.9, which is impractical with passive tuners in D-band. The load-pull contours at 140 GHz were measured for quiescent I_d of 50, 100, and 200 mA/mm and a drain-source voltage of 12 V, covering deep Class AB to Class A operation. The load for peak power-added efficiency (PAE) is ~ $0.7 + 0.5j$, largely independent of bias. The load that maximizes output power (P_{out}) varies with the bias conditions but remains in close proximity to the load corresponding to peak PAE. Power sweeps at the optimal Γ_{load} for peak PAE and P_{out} were analyzed and compared. Under load conditions optimized for PAE, for an I_d of 100 mA/mm, a small-signal gain of 7 dB, with a peak PAE of 19.0% and saturated P_{out} of 19.5 dBm were obtained at 140 GHz. The appreciable gain and efficiency suggest GaN is a viable transistor technology for mm-wave and sub-mm-wave applications.

ED-Thu-B5 - Temperature Stability of Al-rich AlGaN HFET

4. Electronic devices

Do-Hyeong Yeo[1]
Jun-Hyeok Yim[1], Young Chul Choi[1], Hyun-Seop Kim[2], Jin-Hong Lim[3], Ho-Young Cha[1]
[1] School of Electronic and Electrical Engineering, Hongik University, Seoul, Republic of Korea
[2] Department of Electrical Engineering, Kunsan National University, Gunsan, Republic of Korea
[3] ChipsK Corporation, Anyang, Republic of Korea

Abstract text: AlGaN heterostructures with high Al mole fractions have attracted attention due to their excellent temperature stability and high breakdown field, making them suitable for harsh environment power switching applications. In this study, we developed a fabrication process for Al-rich AlGaN HFET($Al_{0.85}Ga_{0.15}N/Al_{0.5}Ga_{0.5}N$) and investigated their temperature-dependent characteristics over a range from room temperature to 300 °C.
As the temperature increased from room temperature to 300 °C, the sheet resistance increased from 7,260 to 14,600 Ω/sq, whereas the specific contact resistance decreased from 8×10^{-3} to 3×10^{-3} Ω·cm^2. The increase in sheet resistance was attributed to enhanced scattering at elevated temperatures, leading to reduced carrier mobility. Due to the non-ideal ohmic contact on the Al-rich AlGaN HFET surface, thermionic emission was enhanced at higher temperatures, effectively lowering the barrier height. As a result, the contact resistance decreased with rising temperature.

Current-voltage characteristics measured between room temperature and 300 °C exhibited excellent stability compared to conventional AlGaN/GaN HEMTs. The maximum drain current of the Al-rich AlGaN HFET decreased by only 11 %, whereas conventional AlGaN/GaN HEMTs showed a reduction of 44 % for comparison. The fabricated Al-rich AlGaN HFET also demonstrated remarkable on-resistance stability across the entire temperature range, increasing by only 7.6% (from 224 Ω·mm at room temperature to 239 Ω·mm at 300 °C).

Notably, the fabricated Al-rich AlGaN HFET exhibited minimal trapping effects under pulsed measurements, despite the absence of surface passivation or a field plate. Unlike conventional AlGaN/GaN HEMTs, the Al-rich AlGaN HFET showed negligible trapping effects, suggesting that the high Al mole fraction in the $Al_{0.85}Ga_{0.15}N/Al_{0.5}Ga_{0.5}N$ barrier created a high-energy barrier that prevented electron injection from the gate. This high-energy barrier also enabled a large maximum forward gate voltage. The maximum positive gate voltage was 9.8 V at room temperature and 8.6 V at 300 °C, indicating a substantial Schottky barrier height.

This research was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(Ministry of Science and ICT) (RS-2024-00431359).

Charge carriers and mobility

2025-07-10
08:30 - 10:00
Charge carriers and mobility

PC-Thu-1 - Fluke or Myth: A Hole Mobility of 1500 cm2/Vs in GaN (though at 4 K)

2. Physics and characterization

H. Grace Xing[1]
[1] Cornell University

Abstract text: The advent of p-type GaN has changed the world forever. To date most of the p-type GaN has been achieved by impurity doping, i.e. replacing Ga with Mg in the GaN semiconductor crystal. The hole mobility in GaN has a typical value of 20 cm^2/Vs at room temperature and 100 cm^2/Vs around 100 K; below 50 K, it is impossible to measure hole mobility in impurity-doped GaN due to severe carrier freeze-out – literally GaN:Mg becomes a semi-insulating materials at these cryogenic temperatures.

In this invited talk, I will discuss our effort of realizing a hole mobility of 1500 cm^2/Vs albeit measured at 4 Kelvin: method, experiments, measurements and forecast. It started from a few years back when Chaudhuri et al [Science 2019] demonstrated that it is possible to form a 2D hole gas at the GaN/AlN interface without impurity dopants, which arises from the discontinuity of polarization at this heterointerface. This 2D hole gas is free from dopant scattering and freeze-out, just like its counterpart – the 2DEG at an AlGaN/GaN interface. As a result, it provides an unprecedented platform for us to probe the valence band of GaN.

(Speaker Bio) Huili Grace Xing is currently the Director of SUPREME - a SRC JUMP2.0 research center, the William L. Quackenbush Professor of Electrical and Computer Engineering, Materials Science and Engineering at Cornell University, and having recently served as the Associate Dean for Research & Graduate Studies of the College of Engineering. She is a recipient of the AFOSR Young Investigator Award, NSF CAREER Award, ISCS Young Scientist Award, and the Intel Outstanding Researcher Award. She is a fellow of APS, IEEE & AAAS.

PC-Thu-2 - Terahertz to mid-infrared Optical Hall effect for probing electronic properties of group-III nitride materials and device heterostructures

2. Physics and characterization

Nerijus Armakavicius[1]
Philipp Kühne[1], Sean Knight[1], Alexis Papamichail[1], Hengfang Zhang[1], Axel Persson[1], Vallery Stanishev[1], Jr-Tai Chen[2], Plamen Paskov[1], Mathias Schubert[3], Vanya Darakchieva[4]
[1] Center for III-Nitride Technology, C3NiT - Janzén, Linköping University, Linköping, Sweden
[2] SweGaN AB, Linköping
[3] Department of Electrical and Computer Engineering, University of Nebraska-Lincoln, Lincoln, U.S.A.
[4] NanoLund, Center for III-Nitride Technology, C3NiT - Janzén, Terahertz Materials Analysis Center, THeMAC and Solid State Physics Division, Lund University, Lund, Sweden

Abstract text: Precise characterization of charge carrier properties in group-III nitride materials and related device structures is essential for their optimization and enhanced performance. Spectroscopic ellipsometry-based optical Hall effect measurements performed at terahertz (THz) and infrared (IR) spectral ranges provide a robust, non-contact, and non-destructive method for probing key electronic properties, including electron effective mass, mobility, and carrier density [1-3]. Unlike conventional contact-based techniques, optical Hall effect enables the investigation of buried conductive layers, offering valuable insights for refining material properties and advancing device development.

In this work, we demonstrate the applicability of THz to mid-IR optical Hall effect for quantitatively analyzing free charge carrier properties in GaN, AlN, and AlGaN materials and device structures relevant to next-generation high-frequency and high-power electronics. We showcase its ability to assess the impact of Al compositional variations on 2DEG properties in AlGaN/GaN HEMTs, investigate anisotropic charge carrier mobility influenced by substrate morphology in N-polar HEMTs, and determine electron effective mass parameters across a wide temperature range in GaN, AlGaN, and InGaN. Additionally, we discuss potential mechanisms contributing to variations in electron effective mass, including band structure effects, electron-phonon interactions, strain, and deviations from classical electron transport models.

References

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PC-Thu-3* - Shedding light on GaN's valence bands using high-mobility holes

2. Physics and characterization

Chuan Chang[1]
Joseph Dill[1], Zexuan Zhang[1], Jie-Cheng Chen[2], Naomi Pieczulewski[1], Samuel Bader[3], Oscar Ayala Valenzuela[4], Scott Crooker[4], Fedor Balakirev[4], Ross McDonald[4], Jimy Encomendero[1], David Muller[1], Feliciano Giustino[2], Debdeep Jena[1], Huili Grace Xing[1]
[1] Cornell University
[2] The University of Texas Austin
[3] Foundry Technology Research, Intel Corporation
[4] National High Magnetic Field Laboratory, Los Alamos National Laboratory

Abstract text: GaN was long thought to be only practically available as an n-type semiconductor until the achievement of p-type doping made blue LEDs and lasers possible, leading to an energy-efficient solid-state lighting revolution. In electronics, the high-mobility two-dimensional electron gas (2DEG) at the AlGaN/GaN heterointerface is enabling energy-efficient RF and power devices [1]; however, the first two-dimensional hole gas (2DHG) in GaN without impurity doping was only reported in 2019 [2]. As GaN holes have lower mobility and are harder to access experimentally, fundamental understanding of the 2DHG has lagged that of the 2DEG. In this talk, we show that beyond pushing the performance of p-channel GaN transistors, record-high mobility holes open a new frontier for fundamental understanding and quantum engineering of GaN's valence bands.

We demonstrate that polarization-doping, without needing Mg dopants, induces enough holes to degenerately occupy two valence bands of GaN – the light hole (LH) and the heavy hole (HH) bands – without thermal freeze-out [3]. Going beyond conventional Hall measurements, we extract band-resolved transport properties of the light and heavy holes as a function of temperature. At 3 K, mobilities of ~1900 cm^2/Vs and ~400 cm^2/Vs for LHs and HHs, respectively, are observed.

Shubnikov-de Haas (SdH) oscillations is one of the most powerful tools in condensed matter physics to directly probe band structures and Fermi surfaces. Despite decades of effort to improve crystal growth and hole doping, it has thus far not been possible to achieve GaN holes with sufficiently high mobility, surviving and electrically contactable at cryogenic temperatures, to exhibit SdH oscillations. Here, we report [4] SdH oscillations of both HHs and LHs and directly measure their effective masses, putting an end to the current lack of consensus in GaN hole masses. We also report an anomalous field-dependence of the LH mass that cannot be explained by band nonparabolicity.

Finally, we discuss strategies beyond crystal growth to push the mobility limits of GaN holes and the crucial role of SdH oscillations in this endeavor.

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PC-Thu-4* - Synchrotron Scanning Photoelectron Microscopy of Polarization-doped AlGaN/GaN Heterostructures

2. Physics and characterization

Nishant Patel[1]
Byeongchan So[1], Minho Kim[2], Alexis Papamichail[2], Rohit Yadav[1], Eleni Charitoudi[1], Erik Lind[3], Vanya Darakchieva[4], Rainer Timm[1]
[1] NanoLund and Dept. of Physics, Lund University, 221 00 Lund, Sweden
[2] Center for III-Nitride Technology, C3NiT-Janzén, Dept. Physics, Chemistry and Biology, Linköping University, 581 83 Linköping, Sweden
[3] NanoLund and Dept. Electrical and Information Technology, Lund University, 221 00 Lund, Sweden
[4] Nanolund and Department of Physics, Lund University, 221 00 Lund, Sweden and Center for III-Nitride Technology, C3NiT-Janzén, Dept. Physics, Chemistry and Biology, Linköping University, 581 83 Linköping, Sweden

Abstract text: Gallium Nitride (GaN) and Aluminum Gallium Nitride (AlGaN) compounds are at the forefront of ultrawide bandgap semiconductor research, with applications in power electronics, radio-frequency (RF) devices, and high-efficiency optoelectronics. In heterostructures, the interfaces enable high carrier densities and mobilities due to strong polarization and charging effects, making them ideal for high-performance electronic devices. In particular, polarization doping, a technique leveraging spontaneous and piezoelectric polarization rather than impurity-based doping, presents an opportunity to engineer charge distribution without introducing extrinsic defects.

Despite its promise, the precise relationship between Al composition gradients, polarization-induced band bending, and local electronic structure remains poorly understood. Addressing this knowledge gap is critical for optimizing next-generation high-power and high-frequency devices.

To investigate these effects, we employed synchrotron-based Scanning Photoelectron Microscopy (SPEM) using a focused X-ray beam with 120 nm spot size. This technique enables mapping core-level shifts associated with compositional variation and polarization-induced band bending with high spatial resolution. Our study focused on cleaved AlGaN/GaN heterostructures with both graded and step-like Al composition changes in the top 1 μm, allowing direct access to cross-sectional electronic structure variations. We acquired element-specific SPEM maps of Ga 3d, Al 2p, and N 1s alongside high-resolution photoelectron spectra at defined intervals (100 nm steps) from the cleaved edge.

Our findings reveal significant core-level shifts across the heterostructure, highlighting the interplay between material composition, band bending, and polarization effects. By analyzing fitted peak intensities and energy positions with spatial resolution, we gain deeper insights into how local charge distributions and band alignment evolve within the heterostructure. These results contribute to a more comprehensive understanding of polarization-induced electronic structure modifications, paving the way for improved material engineering strategies in next-generation high-power and high-frequency semiconductor devices.

PC-Thu-5* - Analyzing carrier energy relaxation and transport under high field from DFT calculations and Monte Carlo simulations

2. Physics and characterization
Han-Sheng Fu[1]
Yuh-Renn Wu[1], **Hao Lee**[1]
[1] Graduate Institute of Photonics and Optoelectronics, National Taiwan University

Abstract text: GaN, a wide bandgap semiconductor with a breakdown field of >3.3 MV/cm, holds great promise for power electronics. However, the valley separation of GaN is still not well characterized. The position of valleys and their E-k relation play a critical role in determining the high-field transport behavior for carrier transport. In this work, we aim to study different valley separations from different measurements or DFT simulations.

We first used Quantum Espresso [1] to calculate the GaN band structure and identify different valley positions. Four lowest valleys were found, and phonon dispersion was presented. The EPW package[2] is used to calculate electron-phonon coupling, identifying contributions from different phonons to scattering rates. Nonpolar optical phonons play a key role in high electron momentum transfer, facilitating intervalley scattering. We extracted deformation potentials from the electron-phonon matrix element at different initial and final states [3] as a reference for scattering rate fitting [4]. Using these extracted parameters, multi-valley Monte Carlo simulations at 300 K and 10^{16} cm^{-3} impurity concentration revealed electron velocity and distribution changes under an electric field along the Γ-M direction.

We obtained a mobility of 1650 $cm^2/V{\cdot}s$, with a peak electron velocity of 3×10^7 cm/s at 200 kV/cm. The electron velocity gradually decreases from 1×10^7 to 5×10^6 cm/s as the electric field increases from 1 to 4 MV/cm. Around 1.5 MV/cm, electrons are pushed by the electric field from the U valley back to the G valley. At 3 MV/cm, most electrons accumulate above 2 eV, with a small 3 eV peak from electrons moving along the field to the flat band region near M point. Furthermore, at 3 MV/cm, 5.76% of electrons exceeded 3.4 eV above the CBM, potentially leading to impact ionization. These insights provide a deeper understanding of the transport properties of GaN. The next step is to apply different valley separations from experimental results to compare the difference between DFT and experiment results.

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N-polar AlN and structures

2025-07-10
10:30 - 12:00
N-polar AlN and structures

GR-Thu-6 - Control of Surface Morphology and Polarity of N-Polar AlN Films Grown on AlN Bulk Substrates

1. Growth

Rafael Dalmau[1]
Samuel Kirby[1], Jeffrey Britt[1], Toru Kinoshita[1]
[1] HexaTech Inc., Morrisville, USA

Abstract text: GaN-based lateral power switching devices are being developed for high-power and high-frequency applications, where they outperform devices based on traditional semiconductors due to favorable material properties, such as a high thermal conductivity and wide bandgap energy. In high electron mobility transistors (HEMTs), the heterostructure possessing a 2D electron gas generated by the polarization discontinuity at the AlGaN/GaN interface possess a high sheet carrier density and mobility, high breakdown voltage, and low on-resistance. Most of of these devices are based on metal polar heterostructures, but N-polar HEMTs are gaining attention since they offer prospects for improved performance. The reversed location of the wider bandgap layer, under the channel, provides enhanced carrier confinement due to the improved back barrier effect, while having the lower bandgap material at the device surface simplifies the fabrication of low resistivity Ohmic contacts. However, epitaxial growth of N-polar III-nitrides and their alloys is challenging since the different surface reconstructions present during growth alter the surface kinetics, with potential adverse consequences to the surface morphology and polar stability. Thus, development of dedicated processes for N-polar growth are required for evolution of this technology.

Bulk AlN grown by physical vapor transport is a promising substrate material for high quality III-nitride epitaxy, offering high electrical resistivity and thermal conductivity, low dislocation density, and an ultra-wide bandgap. N-polar HEMTs grown on N-polar AlN substrates simultaneously benefit from these material properties as well as the advantages of N-polar heterostructures, which may improve the maximum power gain cut-off frequency. While growth of Al-polar AlN and AlGaN films on AlN substrates by MOCVD and MBE is well developed, and a surface kinetics-based model for control of the AlN surface morphology has been presented, growth of N-polar AlN is relatively immature and can suffer from high surface roughness and polarity inversion. In this work, the development of an MOCVD growth process for smooth and uniform N-polar AlN will be presented. Application of surface kinetics concepts in a quantitative and predictive manner for control of the N-polar AlN surface morphology and polarity will be discussed.

GR-Thu-7 - N-polar GaN epilayers grown by molecular beam epitaxy on silicon substrates using an hybrid AlN/NbN buffer layer

1. Growth

Antoine Pedeches[1]
Hélène Rotella[1], Iléana Floréa[1], Philippe Vennégues[1], **Fabrice Semond**[1]
[1] Université Côte d'Azur, CNRS, CRHEA

Abstract text: The epitaxy of N-polar GaN epilayers has become a subject of strong interest today, particularly for the fabrication and study of high electron mobility heterostructures (HEMTs) for microwave applications [1]. Significant progresses have been made in recent years on Silicon Carbide and Sapphire substrates in order to obtain good quality N-polar GaN structural properties with low surface roughness and low impurity concentration [2]. On Silicon substrates, which remains a substrate of choice for applications in the field of electronics, there are a few rare demonstrations of obtaining nitrogen polarity [3-5] but no robust and competitive N-polar HEMTs devices were produced on Si. This work presents an original approach to grow by ammonia-molecular beam epitaxy (NH_3-MBE) N-polar III-N epilayers on silicon substrates using a hybrid AlN/NbN (niobium nitride) buffer. This study presents the growth conditions mandatory to control the polarity conversion from metal-polar to nitrogen-polar using a few NbN epitaxial monolayers. Using transmission electron microscopy, the hybrid stack (Si/Al-AlN/NbN/N-AlN) is studied to understand the role of interfaces and to optimize the buffer layer stack. This buffer is used to study (DRX, AFM, SIMS) and optimize the growth conditions of N-polar GaN on silicon substrate. As already reported [6], this study shows that N-polar GaN can and must be grown at high temperatures (above 900°C) in order to improve the structural quality and decrease the impurity concentration. Under these growth conditions and for comparable thicknesses, the structural quality of N-polar GaN on silicon is even better than metal-polarity GaN grown on Si. The impurity concentration decreases significantly by increasing the growth temperature. A carbon atom concentration below 10^{16} cm^{-3} is achieved, however the oxygen atom concentration is still high, typically in the low 10^{17} cm^{-3}. The surface roughness of N-polar GaN is relatively high (rms >5 nm), however, preliminary assessments of growth on off-axis silicon substrates show that the roughness can be significantly reduced (rms <2 nm). This improvement of the growth front roughness is very promising to further reduce the concentration of impurities. We conclude this study by presenting the first N-polar HEMTs on silicon substrates showing very encouraging characteristics.

GR-Thu-8 - Low contact resistivity of N-polar p++-GaN enabled by N-rich conditions in plasma-assisted molecular-beam epitaxy

1. Growth

YongJin Cho[1]
Kazuki Nomoto[2], Huili Grace Xing[2], Debdeep Jena[2]
[1] Cornell University, Ithaca, New York 14853, USA and Paul-Drude-Institut für Festkörperelektronik, 10117 Berlin, Germany
[2] Cornell University, Ithaca, New York 14853, USA

Abstract text: In wurtzite III-nitride heterostructures, the N-polar direction is as important as the metal polar one and is advantageous for its own unique applications in devices such as buried-barrier high electron mobility transistors, interband tunnel junctions and resonant tunnelling diodes. From the perspective of the MBE growth of GaN, the two surface polarities behave quite differently: the contracted Ga bilayer, which is beneficial for boosting the diffusion length of the adatoms and resulting in smooth surface morphology in GaN growth, is *unstable* on the N-polar surface, which often leads to kinetically driven morphological instabilities. It is also known that under a fixed MBE growth condition, the N-polar growth exhibits higher unintentional O donor incorporation and much lower Mg acceptor incorporation, by almost an order of magnitude, compared to Ga-polar counterpart, which can thus lead to high *p*-contact resistivity of N-polar *p*-GaN.

In this work, we demonstrate that N-rich growth conditions in MBE enhance Mg incorporation in GaN, leading to a considerable decrease in the contact resistivity of N-polar *p*-GaN. Two N-polar *pn* diodes were grown on N-polar n^{+}-GaN bulk substrates with a p^{++}-GaN layer on top. Most layers in both samples were grown under nominally identical and Ga-rich conditions. The only difference between the two samples was that one had the *p*-GaN region grown under Ga-rich conditions, while the other had it grown under N-rich conditions.

CTLM revealed that the specific contact resistivity and sheet resistivity of the top *p*-GaN region were $2.7\text{x}10^{-3}$ Ω cm^2 and $6.8\text{x}10^{4}$ Ω/sq for the Ga-rich grown sample, and $3.4\text{x}10^{-4}$ Ω cm^2 and $1.3\text{x}10^{5}$ Ω/sq for the N-rich grown sample, respectively. Both diodes indicate turn on near the expected built-in potential and show ultralow leakage below ~2 V bias. But the nearly one order of magnitude lower contact resistivity in the *pn* diode with N-rich grown *p*-GaN resulted in a significant, nearly 2- to 4-fold increase in current density under forward bias compared to the diode with Ga-rich grown *p*-GaN for forward bias voltages above the built-in bias.

These results indicate that N-rich growth conditions are highly effective in reducing the contact resistivity of *p*-GaN contact layers and could be a convenient approach for the formation of ohmic contacts in *p*-type nitrides, particularly for N-polar *p*-channel devices.

GR-Thu-9* - N-polar AlN/GaN high electron mobility transistor grown by MOVPE on sapphire

1. Growth
Itsuki Furuhashi[1]
Xu Yang[1], Markus Pristovsek[1], Chengzhi Zhang[2], Martin Kuball[2], Matthew D. Smith[2]
[1] Nagoya University
[2] University of Bristol

Abstract text: N-polar AlN-based high electron mobility transistors (HEMT) are studied as a next generation device structure with the AlN barrier layer below the GaN channel, so high Al contents are possible without impairing the Ohmic contact, giving a higher 2-dimentional electron gas (2DEG) density than in typical metal-polar or N-polar HEMTs based on GaN.

There were only a few prior investigations due to the challenging growth of N-polar AlN-based HEMT structures by metal-organic vapor phase epitaxy (MOVPE). Only recently, it was found that smooth AlN layers can be grown using very low V/III ratios like ~1.75 on 4° misoriented sapphire.

The GaN channel layer in such templates showed a strong tendency to develop step-bunching. To overcome this, we varied the growth temperature. We found that 800±50 ˚C resulted in the smoothest surfaces with roughnesses of 0.5 nm or lower. On the impurity incorporation, using tri-ethyl Gallium as the Ga source gas can reduce carbon incorporation to 10^{17} $cm^{-3,}$ even at T ≤850 ˚C. Using high V/III ratios for the GaN channel growth also resulted in below 10^{17} cm^{-3} oxygen concentration.

However, oxygen is incorporated in the N-polar AlN at a concentration of ~10^{19} cm^{-3} and reaching close to 10^{20} cm^{-3} at the AlN/GaN interface during the long growth interruption from low V/III ratio and high temperature AlN growth to low temperature and high V/III ratio GaN growth. Thus, an AlN transition layer was inserted in which the V/III ratio was increased and growth temperature decreased while keeping the roughness small. This reduced the sheet resistance from over 100 kΩ to ~800 Ω. For all samples with a coherent N-polar GaN channel to AlN buffer, the 2DEG density was always close to ~4x10^{13} cm^{-2} which is the expected value from theory, independent of channel thickness. While the sheet resistivity is strongly related to the channel thickness, the surface roughness is not related to it. Thus, thickening channel is good for increasing the mobility in this thin channel structure.

Using our sample structure, p-gated normally-off HEMT were fabricated. A p-type NiO_x gate stack layer was sputter-deposited, sitting between the GaN channel layer and Ni/Au gate metallization, but not in the access regions between the gate and Ohmic contacts. This depleted the 2DEG in the channel, providing gate control and resulting a normally-off transistor characteristic.

GR-Thu-10 - High-density two-dimensional hole gases on the GaN/AlGaN/GaN platform enabled by heterostructure band engineering

1. Growth

Pengfei Shao[1]
Yu Liu[1], Qi Yao[1], Hui Guo[1], Tao Tao[1], Zili Xie[1], Bin Liu[1], Dunjun Chen[1], Youdou Zheng[1], Rong Zhang[1], Ke Wang[1]
[1] Nanjing University, Nanjing, P. R. China

Abstract text: High-density two-dimensional hole gases on the GaN/AlGaN/GaN platform enabled by heterostructure band engineering

Pengfei Shao[1], Yu Liu[1], Qi Yao, Hui Guo[1], Tao Tao[1], Zili Xie[1], Bin Liu[1], Dunjun Chen[1], Youdou Zheng[1], Rong Zhang[1], Ke Wang[1,*]

[1] Nanjing University, Nanjing, P. R. China

**E-mail: kewang@nju.edu.cn*

Two-dimensional hole gas (2DHG) induced by polarization charges at the GaN/AlGaN hetero-interface is attracting much attention because of its potential to develop p-channel transistors required for GaN complementary logic (CL) circuits. This platform is often compatible with the mature E-mode p-GaN gate HEMT technology and is easy to implement CL circuits. But the current density of these p-FETs on such platform is small due to the low 2DHG density.

From the perspective of energy band engineering for III-nitride heterostructures, we have found various ways to increase the 2DHG density on the GaN/AlGaN/GaN platform, by modulating the energy band profiles around the 2DHG. (1) The 2DHG density was effectively enhanced to 2.71×10^{13} cm^{-2} at 300 K, by introducing extra Mg acceptors in the middle of AlGaN barrier layer, which lifts upward the valence band (VB) around the hole channel near the upper heterointerface (UHI). (2) The 2DHG density increases with raised AlN thickness from 2.87×10^{13} cm^{-2} without AlN to 4.5×10^{13} cm^{-2} for 3 nm AlN at 300K. This is attributed to the lifted-up energy bands around UHI relative to the Fermi level (E_F). Therefore, the technology for energy band engineering demonstrated in this work has proved an effective approach to enhance 2DHG density. The 2DHG density is 5.6×10^{13}, the mobility reaches 28 $cm^2/V\cdot s$, and a record low sheet resistance of 4.7 kΩ/□ is obtained, which is attributed to improving the GaN/AlN interface by using the combination of Al modulation epitaxy and Ga as a surfactant (AMEGS) growth method grown AlN interlayer. Therefore, the technology for energy band engineering demonstrated in this work has proved an effective approach to enhance 2DHG density.

Visible lasers

2025-07-10
10:30 - 12:00
Visible lasers

OD-Thu-6 - Nitride edge emitters on 3D shaped GaN - adjustable properties and smart integration options

3. Optical devices

Anna Kafar[1]
Adam Brejnak[1], Szymon Stanczyk[1], Conny Becht[2], Zhaozong Zhang[3], Takao Oto[4], Lucja Marona[1], Kiran Saba[1], Szymon Grzanka[1], Ryota Ishii[3], Mitsuru Funato[3], Yoichi Kawakami[3], Ulrich Schwarz[2], Piotr Perlin[1]
[1] Institute of High Pressure Physics PAS, Warsaw, Poland
[2] Chemnitz University of Technology, Chemnitz, Germany
[3] Kyoto University, Kyoto, Japan
[4] Yamagata University, Yonezawa, Japan

Abstract text: The technology of nitride semiconductor emitters is constantly evolving, addressing the requirements of existing applications and even inspiring new ones. The main approaches to device development involve either perfecting existing methods or exploring alternative solutions. This work focuses on the latter. We utilize a non-flat substrate with intentionally created 3D structures on its surface to enhance emitter performance or introduce new functionalities. Specifically, we are investigating substrate patterning for a wide range of emitter types, including laser diodes, superluminescent diodes, waveguides coupled to lasers, laser arrays, and micro-LEDs.

One key effects utilized by us is the strong dependence of indium incorporation into InGaN layers on the local substrate off-cut. Typically, achieving high uniformity in emission wavelength and other parameters requires precise substrate preparation, including a uniform, small off-cut of the wafer relative to the crystallographic plane. However, in our experiments, we intentionally introduce significant off-cut variations—for example, increasing the local off-cut by 2° - to locally widen the bandgap. This allows for lateral bandgap tuning, providing a new and valuable degree of freedom. One notable application is the creation of superluminescent diodes with broadened emission spectra. By introducing an off-cut gradient along the device waveguide, we have achieved more than a threefold increase in spectral width. Additionally, by creating areas with a larger off-cut, we can form waveguides that are transparent to light generated in adjacent regions. This concept has been successfully applied in the fabrication of laser diodes with integrated non-absorbing waveguides, formed within the same epitaxial structure.

There are also other potential applications of substrate patterning. With careful patterning, we can integrate micromirrors directly into the laser structure, redirecting the output beam of an edge emitter to create a quasi-surface-emitting laser array. Furthermore, micro-scale 3D features can be used to locally modify growth conditions. Our results indicate that locally grown quantum wells can exhibit significantly improved emission intensity, homogeneity, and defect reduction. These features may help to mitigate the effects responsible for the notorious “green gap” problem in nitride light emitters.

OD-Thu-7 - Air- and porous-claddings for blue laser diodes

3. Optical devices

Marta Sawicka[1]
Oliwia Gołyga[1], Mateusz Hajdel[1], Anna Kafar[1], Henryk Turski[1], Mikołaj Chlipała[1], Marcin Siekacz[1], Anna Feduniewicz-Żmuda[1], Czesław Skierbiszewski[1], Grzegorz Muziol[1]
[1] Institute of High Pressure Physics PAS

Abstract text: Electrochemical etching (ECE) enables new functionalities in III-nitride laser diodes (LDs), thanks to the possibility to tailor the refractive index of the selected layers down to $n_{air} = 1$. Porous GaN can thus replace "classical" AlGaN claddings and confine light more efficiently. Moreover, porous GaN is also perfectly lattice matched to GaN substrate, which is of high importance for long- and short-wavelength LDs, in which the strain engineering matters even more, and light confinement becomes more challenging. ECE can enable also air-cladding LD architecture provided that sufficiently high doping is used in the sacrificial layer.

This work will summarize the applications of porous GaN as a bottom cladding in electrically pumped LDs [1-3]. Furthermore, we will present blue LDs with bottom and top air-cladding. In the first part, we will discuss the impact of the integration of porous layer on the LD performance. Increased internal losses and blue-shift of the emission wavelength was observed. The losses for porous-cladding LD measured by the Hakki-Paoli method were estimated to be 68 cm^{-1}, while for standard LD from the same wafer, the losses were 25 cm^{-1} [2].

Secondly, we will show LDs with air-claddings on both sides of the active region. Structural and optical characterization of the devices operating in pulse mode will be presented. Bottom air-cladding is done by full removal of a sacrificial layer using ECE. The air-cladding at the top is provided by the use of tunnel junction (TJ) enabling positioning of the top metal contact away from the ridge.

Plasma-assisted molecular beam epitaxy (PAMBE) is used in this work as the key technology to fabricate air-cladding LDs as it enables the growth of extremely highly doped InGaN:Ge++ layers with Ge doping ranging from [Ge]=2.5 to 7.5×10^{20} cm^{-3} [4]. Such layer can be easily removed by ECE. PAMBE technology is also used to successfully grow low-voltage TJs that are needed for top air-cladding architecture.

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4. H. Turski et al. Materials 15(17) (2022).

OD-Thu-8 - Blue laser diodes with active-passive waveguides for improved facet stability against catastrophic damage

3. Optical devices
Marco Rossetti[1]
Marco Malinverni[1], **Antonino Castiglia**[1], Marcus Dülk[1]
[1] EXALOS AG, Schlieren, Switzerland

Abstract text: Visible laser diodes based on GaN semiconductors have been the focus of intense research over the past two decades, leading to significant advancements in expanding the range of available wavelengths and enhancing the power output of commercial devices. More recently, specialty laser designs have attracted growing interest, opening new possibilities for innovative applications and performance improvements.

Here, we present experimental data on single-mode Fabry-Perot laser diode devices fabricated using a two-step overgrowth geometry, incorporating a combination of light-emitting and passive waveguiding sections. The epitaxial structure of the active sections includes conventional InGaN/AlGaN waveguides and InGaN multiple quantum wells emitting near 450 nm, while the passive sections share the same substrate and n-side cladding architecture but feature an unintentionally doped top cladding layer and a core region without active layers.

The active-passive architecture enables the development of advanced laser designs, like for example distributed Bragg reflector lasers that have gratings over the passive section or high-power lasers with non-absorbing mirror regions to enhance robustness and lifetime. Additionally, the technology facilitates integration at the wafer level, which has broad implications in photonic circuits.

Single transverse mode devices with non-absorbing facets were fabricated in this work using narrow ridge-waveguide architectures. Higher robustness at high optical power density was achieved using 50 µm-long passive sections on both laser facets. A comparative analysis with standard Fabry-Perot lasers shows a 2.6x increase in the output power required to induce catastrophic mirror damage, confirming the enhanced stability of the non-absorbing mirror sections against photon-induced facet degradation and catastrophic failure. Test structures where also realized with active sections as short as 100 µm, in combination with passive sections of variable length (200 to 500 µm). Through the analysis of threshold and slope efficiencies of these structures, we estimate the optical loss in the passive sections to be below 2 cm^{-1}, and the coupling loss at the active-passive interface under 2%.

These results highlight the potential of active-passive architectures for application in high-power lasers or other advanced GaN laser diode structures.

OD-Thu-9* - Dynamical investigation of stacked multi-junction laser diodes interconnected by tunnel junctions

3. Optical devices

Jannina Tepaß[1]
Mateusz Hajdel[2], Grzegorz Muziol[2], Ulrich T Schwarz[1]
[1] Insitut of Physics, Chemnitz University of Technology, Chemnitz, Germany
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: Stacked multi-junction laser diodes (LDs) consist of several active regions, each embedded in its own waveguide. The in-series pn-junctions are connected via tunnel junctions (TJs) to allow a vertical current flow. This concept enables blue multi-junction LDs with n larger slope efficiencies, where n is the number of stacked individual LDs. Slope efficiencies of 1.4W/A and 2.3W/A have been demonstrated for 2-junction [1] and 4-junction stacked LDs [2]. These stacked LDs have been grown by plasma-assisted molecular beam epitaxy, as technology allows activation of buried TJs [2].
We investigate the optical and electrical dynamics of these devices. Depending on the vertical spacing between stacked LDs, given by the combined cladding thickness, and the gain peak of the individual LDs, the multiple LDs of a stack can be incoherently or coherently coupled. This influences the far-field of the stacks, but also the overlap of the guided mode wavefunction with the TJs, increasing internal losses. Regarding electrical behavior, the TJs not only add to the forward voltage, but also affect device capacity and thus switching time. We analyze multi-junction LDs that consist of two InGaN QWs the same epitaxial structure, emitting in the blue wavelength range (λ=453-459nm). Our dynamical analysis is based on time-dependent and spectrally resolved measurements with streak camera investigations. We are focused on the electrical and optical characterization of stacked LDs and their individual components in short pulse operation. The observations of these devices are compared with optical mode simulations and with an equivalent circuit description of the electronic properties. In particular, we are investigating the influence of potential optical mode coupling with different spacing between the two LDs. A particular property of the multi-junction LDs are long lasting relaxation oscillations that can be stable for different carrier densities and pulse lengths. In the electrical behavior we observe additional current peaks at rising and falling edges of a few 10ns long driving pulse, with sub-nanosecond rise and fall time. We tentatively explain this by the contribution of the TJs to the device capacity.
[1] M. Siekacz et al., OE 27 (2019)
[2] M. Siekacz et al., Electronics 9 (2020)
Research funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)–544925332

OD-Thu-10 - GaN-based violet laser diodes utilizing (In)GaN underlayers

3. Optical devices

Johannes Enslin[1]
Martin Guttmann[1], Saad Makhladi[1], Carsten Netzel[1], Erik Freier[1], Sven Einfeldt[1], Markus Weyers[1]
[1] Ferdinand-Braun-Insitut (FBH), Berlin, Germany

Abstract text: Atomic clocks based on rubidium spectroscopy are one of the building blocks of a precise satellite-based positioning system. Ideally, these clocks would be realized with an external cavity diode laser emitting at 420 nm using a GaN-based ridge waveguide (RW) gain chip. Due to the space environment, long lifetimes are required for these gain chips.
In order to maximize the lifetime a low defect density in the active region is desired. Threading dislocations are mainly determined by the GaN substrates which typically have a dislocation density of 10^4-10^5 cm^{-2}. However, point defects in the active region play a major role as non-radiative recombination centers and need to be reduced. For blue-violet light emitting diodes InGaN or InAlN underlayers below the active region have been proven to increase the radiative recombination efficiency (RRE) drastically. An increase of the thickness of the InGaN underlayer as well as its In-content were shown to be beneficial. Recently, it was found that GaN underlayers grown at similar growth conditions as InGaN layers can increase the RRE as well.
We investigated the use of (In)GaN underlayers grown by metal organic vapor phase epitaxy for RW laser diodes (LDs) emitting at 420 nm. In a first step, the photoluminescence intensity at 10 K and 300 K was compared for multiple quantum well structures grown on top of a 60 nm $In_{0.06}Ga_{0.94}N$ underlayer, a GaN underlayer grown at similar conditions, and a GaN layer grown at a higher temperature, respectively. An 85-fold and 6-fold increase of the room temperature PL intensity was observed for structures with low temperature InGaN and GaN underlayers, respectively, in comparison to structures with high temperature GaN underlayer. Following this result, full LD heterostructures where grown with $In_xGa_{1-x}N$ underlayers (x between 0% and 4%). On-wafer electroluminescence measurements show an increase of the spontaneous emission with increasing In-content of the InGaN underlayer, illustrating the increased RRE. After processing these wafers into broad area LDs, the threshold current density of devices with a stripe width and resonator length of 40 µm and 1.3 mm, respectively, was evaluated in pulsed operation. A reduced threshold current density of 2.8 kA cm^{-2} is observed for In-contents around 2.5% in comparison to a threshold current density above 4 kA cm^{-2} for LDs with GaN underlayer.

Novel Electronic Devices 3 (Materials)

2025-07-10
10:30 - 12:00
Novel Electronic Devices 3 (Materials)

ED-Thu-A6* - Scattering Mechanism of 2DEG in ScAlN/GaN Heterostructures Grown by Plasma-Assisted Molecular Beam Epitaxy

4. Electronic devices

Kouei Kubota[1]
Yusuke Wakamoto[1], Takahiko Kawahara[2], Shigeki Yoshida[2], Kozo Makiyama[2], Ken Nakata[2], Ryosho Nakane[1], Takuya Maeda[1]
[1] The University of Tokyo, Dept. of Electrical Engineering and Information Systems, Tokyo, Japan
[2] Sumitomo Electric Industries Ltd., Transmission Devices Laboratory, Yokohama, Japan

Abstract text: ScAlN is attractive as a barrier layer of a GaN HEMT, owing to its strong polarization and capability of epitaxial growth on GaN. The mobility of the 2DEG in ScAlN/GaN is not high enough (~300 cm^2/Vs), and the scattering mechanism is still unclear [1, 2]. In this study, we prepared ScAlN/GaN heterostructures by PAMBE, and the transport properties were investigated.

Four samples with Sc compositions of 3–17% and ScAlN barrier thickness of 4–6.6 nm were prepared, confirmed by EDS and XRR, respectively. The in-situ RHEED patterns along the [-12-10] axis observed before and after the ScAlN growth showed the sharp streaks with the consistent spacings, indicating the atomically smooth surface and coherent growth. The RMS of 0.36 nm was obtained by AFM.

Hall effect measurements were performed. The sheet electron density (n_s) of $2.0–3.1\times10^{13}$ cm^{-2} were obtained, which did not clearly depend on the Sc compositions. This is reasonable, since the total polarization is almost the same for the Sc composition range [3]. The electron mobility (μ) of 468 cm^2/Vs was obtained, which is the highest value among MBE-grown ScAlN/GaN without an AlN spacer [1, 4].

Temperature-dependent Hall effect measurements were performed from 2 K to 400 K. The n_s was almost constant (3.0×10^{13} cm^{-2}) at all the temperatures, indicating that the 2DEG is induced only by the polarization effect. The μ was 414 cm^2/Vs at 300 K, and increased and saturated as temperature decreased. Interface roughness (IR), polar optical phonon (POP), and acoustic deformation potential (ADP) scatterings were considered for the analyses. At low temperatures, the strong IR scattering owing to the relatively rough interface (Λ/δ=4.9) is the dominant scattering factor. Another group reported an AlN spacer can make smoother interface to enhance μ [1]. At room temperature, μ is limited by IR and POP. The theoretical model shows good agreement with the experimental data using the heavier effective mass of $0.24m_0$, due to non-parabolicity of the conduction band for high n_s. These results are useful to understand the transport properties of 2DEG in ScAlN/GaN for HEMT applications.

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ED-Thu-A7* - E-Mode GaN/AlGaN p-MOSFETs with IDS＞110 mA/mm Enhanced by Tunnel Junction S/D Contacts

4. Electronic devices

Zhaofeng Wang[1]
Zhihong Liu[1], Xiaojin Chen[1], Hanghai Du[1], Hong Zhou[1], Weichuan Xing[1], Weihang Zhang[1], Xiangdong Li[1], Jincheng Zhang[1], Yue Hao[1], **Xin Feng**[2]
[1] State Key Laboratory of Wide-Bandgap Semiconductor Devices and Integrated Technology, School of Microelectronics, Xidian University, Xi'an 710071, China
[2] Xidian University

Abstract text: E-mode GaN-on-Si power HEMTs based on a p-GaN/AlGaN/GaN heterostructure have achieved commercial success in the applications of consuming electronics such as mobile chargers and are also attractive for other scenarios including electric vehicles, industry power sources etc. At the present stage, GaN power electronics are mainly in forms of discrete devices, which rely on external Si integrated circuits to drive. A compact monolithic integration of GaN power devices, logics and drivers are highly desired, as it can not only reduce the area and volume of the power modules but also eliminate the parasitic inductance from the bonding wires between chips, which is easy to cause voltage instability and hinder the full potential utilization of the advantage of GaN HEMTs. However, the research and development of GaN complementary logic integrated circuit (CMOS) is still in its early stage, and one of the main challenges suffered is the lack of high-performance GaN p-channel FETs. Limited by the low mobility and the low carrier concentration of the p-GaN channel, and the high source/drain (S/D) contact resistance, GaN p-FETs typically have a much lower current density compared to the n-FETs.

In this work, we present E-mode GaN/AlGaN p-channel MOSFETs with excellent performance by introduction of polarization induced tunnel junctions to enhance the source/drain (S/D) contacts and lateral current spreading in the access regions. The tunnel junction structure consisting of P^{++}-GaN/InGaN/N^{++}-GaN layers leads to a low contact resistivity (ρ_C) of 1.17×10^{-5} Ω-cm^2 for the P-GaN channel. The fabricated GaN p-MOSFET has a threshold voltage (V_{th}) of -0.86 V, a high drain current (I_{DS}) up to 115 mA/mm, a low on-resistance (R_{on}) of 52.6 Ω·mm, and an ON/OFF current ratio (I_{ON}/I_{OFF}) of 7.2×10^4. The monolithically fabricated GaN power high electron mobility transistor (HEMT) shows a breakdown voltage (BV) more than 1700 V. The proposed technology of GaN p-MOSFETs was promising in the applications of GaN logic and drivers for all-GaN monolithic power integrated circuits.

The authors would like to thank the fabrication tool support from the Guangzhou Wide Bandgap Semiconductor Innovation Center.

ED-Thu-A8 - Ultra-Wide Threshold Voltage Tuning Achieving E-Mode AlN/GaN-on-Si HEMTs Enabled by Passivation Engineering on 1.3 nm Ultra-Thin Barrier

4. Electronic devices

Siyu Liu[1]
Yihao Zhuang[1], Hanchao Li[2], Qingyun Xie[3], Hanlin Xie[3], Geok Ing Ng[2]
[1] Energy Research Institute, Nanyang Technological University, Singapore
[2] School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore
[3] National GaN Technology Centre, Agency for Science, Technology and Research, Singapore

Abstract text: This work reports a novel enhancement-mode AlN/GaN HEMT on Si, utilizing passivation-induced stress to modulate the polarization strength of an ultra-thin (1.3 nm) AlN/GaN structure. This approach enables a 20 V threshold voltage tuning range (+18 V to −2 V). With SiN passivation, sheet resistance (R_s) decreases from 5000 Ω/sq to 660 Ω/sq, while saturation current rises from 10 mA/mm to 800 mA/mm. The process eliminates etching reliability concerns, offering a promising RF E-mode HEMT solution.

The cross-section comprises, from top to bottom, a 1.6 nm *in-situ* SiN, 1.3 nm AlN barrier, GaN channel, GaN buffer, and Si substrate. The device adopts a floating-gate structure (L_G = 150 nm) encapsulated by PECVD-SiN. Contact and sheet resistance vary with passivation thickness: for 30 nm, R_c = 0.5 Ω·mm and R_s = 2240.3 Ω/sq; for 50 nm, R_c = 0.27 Ω·mm and R_s = 1403 Ω/sq; for 60 nm, R_c = 0.4 Ω·mm and R_s = 660 Ω/sq. Thicker passivation reduces R_s, indicating enhanced piezoelectric polarization and increased carrier concentration. Transfer characteristics show drain currents (threshold voltages) of 14 mA/mm (18.2 V) without SiN and 820 mA/mm (-0.6 V) with SiN.

The stress mechanism is analyzed through heterojunction atomic structure and bonding. GaN induces tensile stress in AlN due to lattice mismatch, while amorphous SiN passivation further introduces tensile stress via thermal expansion mismatch, forming stress during post-annealing cooling. Under tensile stress, AlN's piezoelectric polarization aligns opposite to [0001], varying with applied stress. Raman peak shifts confirm this effect: AlN without in-situ SiN peaks at 656.58 cm^{-1}, shifting to 655.98 cm^{-1} with 1.6 nm *in-situ* SiN and to 654.36 cm^{-1} with 50 nm PECVD-SiN, demonstrating weaker tensile stress in thinner *in-situ* SiN. This highlights the significant impact of SiN thickness and growth temperature on stress magnitude.

Systematic testing reveals that increasing passivation thickness shifts V_{th} negatively, enhances saturation current, and reduces R_s. Small-signal testing of an E-mode HEMT with 50 nm SiN (V_{th} = 0.3 V) shows f_T = 26 GHz and $fmax$ = 45 GHz.

In summary, this work demonstrates stress control in ultrathin AlN barriers via SiN thickness tuning in a free-etch process, effectively modulating R_s, V_{th}, and saturation current. This provides a simpler, more reliable RF E-mode HEMT fabrication method.

ED-Thu-A9 - Epitaxy of AlGaN channel HEMT for extreme environmental electronics : challenges and solutions

4. Electronic devices

Okhyun Nam[1]
Jooyong Park[1], Shyam Mohan[1], Joocheol Jeong[1], Joonhyuk Lee[1], Jaejin Heo[1]
[1] Department of Semiconductor Engineering, Tech University of Korea (TU-Korea), Siheung, Gyeonggi 427-793, Republic of Korea.

Abstract text: AlGaN/AlGaN channel High Electron Mobility Transistors (HEMTs) are emerging as promising devices for extreme environmental electronics, offering several advantages over traditional AlGaN/GaN channel HEMTs.

The wider bandgap of AlGaN compared to GaN allows AlGaN channel HEMTs to achieve higher breakdown voltages, making them suitable for high-power applications. Also, AlGaN channel HEMTs exhibit superior performance and potential for high-frequency applications at elevated temperatures. For instance, devices with higher aluminum content in the channel demonstrate reduced mobility degradation with increasing temperature, maintaining better operational stability in extreme thermal conditions.

However, the growth of Al-rich AlGaN layers on AlN buffers presents notable challenges. Residual lattice mismatch between AlN and AlGaN induces significant strain, leading to surface morphological degradation, such as increased surface roughness and defect formation. These issues degrade the crystalline quality of the AlGaN layer, adversely impacting electron mobility, increasing device leakage currents, and limiting device performance.

In this study, we have suggested the growth challenges and possible solutions of Al-rich AlGaN channel HEMT. To improve the crystal quality and performance of the HEMT, we have introduced novel epitaxial technologies such as the AlN/AlGaN superlattice (SL) structures and pulsed flow growth. We would like to present and discuss the results of improving the crystal quality and performance of the AlGaN channel HEMT device by the implementation of these new epitaxial technologies.

Acknowledgement:

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ED-Thu-A10* - Enhanced InAlN/GaN MISHEMTs based on digital wet etching process of gate-recess

4. Electronic devices

Congwei Tang[1]
Zhihong Liu[2], Zeyu Song[2], Hanghai Du[2], Jincheng Zhang[2], Yue Hao[2], **Xin Feng**[3]
[1] Guangzhou Institute of Technology, Xidian University, Guangzhou, China
[2] School of Microelectronics, Xidian University, Xi'an, China
[3] Guangzhou Institute of Technology, Xidian University

Abstract text: Enhancement-mode (E-mode) devices are the best choice for various application scenarios such as mobile terminals and wireless communications. Among the main technical routes to realize E-mode, metal-insulator-semiconductor high-electron-mobility-transistor (MISHEMT) based on gate-recess structure are relatively simple to prepare, and the threshold voltage, transconductance and other device performances are relatively high. However, there are still problems such as high etching surface damage and difficult to control etching depth, especially for InAlN/GaN heterojunction structure with thin barrier layer thickness.

In this work, we report a digital wet etching process technology tailored for InAlN materials. This technology employs a recurring cycle of surface oxidation followed by wet removal of the oxide layer. It uses O_2 plasma in Plasma Enhanced Atomic Layer Deposition (PEALD) chamber to oxidize the surface of InAlN materials, and then removes the oxide layer through wet etching, thereby achieving etching of InAlN materials in a controlled manner. The etching depth increases linearly with increasing number of etching cycles, demonstrating the controllable and accurate etching of the digital wet etching process with an etching rate of approximately 0.38 nm/cycle. Compared to dry etching under the same conditions, the time constant is in the microsecond (μs) range, and the trap energy levels are relatively shallow. Among them, the traps in both types of devices are mainly fast-state traps. Within the same time constant range of 0.5 to 3.5 μs, the interface state density of devices subjected to digital wet etching is reduced by approximately 14% compared to those etched by dry methods, resulting in a lower interface state density.

Using the digital wet etching process technology, high performance E-mode InAlN MIS-HEMT devices based on gate-recess have been successfully fabricated. The fabricated devices have gate length of 3 μm, gate width of 100 μm, trench width of 2 μm, source-to-drain spacing of 12 μm, and a 10 nm Al_2O_3 gate oxide layer. The device achieves a V_{TH} of 2 V, an I_{DMAX} of 338 mA/mm, a G_m of 113 mS/mm, and a R_{on} of 12.3 Ω·mm. The interface state density estimated using the high-frequency conductance method was 3.4×10^{13} cm^{-2}/eV to 3.8×10^{13} cm^{-2}/eV, with time constants ranging from 0.8 to 2.2 μs.

Vertical Power Devices 1 (Materials)

2025-07-10
10:30 - 12:00
Vertical Power Devices 1 (Materials)

ED-Thu-B6 - GaN-on-GaN Devices for Next Generation Electronics

4. Electronic devices

Jun Suda[1]
[1] Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan

Abstract text: AlGaN/GaN high-electron mobility transistors (HEMTs) are now widely used in base stations, radar systems, and USB power adapters. These devices are typically fabricated using AlGaN/GaN(0001) heterostructures grown on foreign substrates such as SiC(0001), Si(111), or sapphire(0001). Although these heteroepitaxial layers contain a high density of threading dislocations along the [0001] direction (10^8–10^9 cm^{-2}), the devices perform reliably because both the current flow and the electric field are oriented perpendicular to the dislocation lines. AlGaN/GaN HEMTs on foreign substrates have demonstrated superior performance compared to conventional Si- and GaAs-based devices, thanks to outstanding material properties of GaN — namely, its large critical electric field and excellent two-dimensional electron gas (2DEG) characteristics. However, for vertical GaN power devices, high-quality GaN homoepitaxial layers are essential, as threading dislocations penetrating the p–n or Schottky junctions lead to excessive leakage currents.

Our group has investigated the fundamental properties of GaN layers grown on native GaN substrates, along with key device process technologies such as ion implantation and MOS interface control for GaN-on-GaN materials. In this presentation, we will discuss the current status and future prospects of GaN-on-GaN vertical power devices.

Although GaN HEMTs on foreign substrates function effectively, their performance remains below the theoretical limits of GaN devices due to dislocation-related degradation. To address this, our group has explored GaN-on-GaN HEMTs, including the development of semi-insulating GaN substrates in collaboration with Mitsubishi Chemical Corporation. Our recent results and insights on these efforts will also be presented.

Currently, GaN substrates are more expensive than other commonly used substrates. However, over the past two decades, significant progress has been made in GaN bulk substrate technologies, leading to substantial improvements in both wafer size and crystal quality. As mass production becomes more feasible, substrate costs are expected to decrease. GaN-on-GaN technology is poised to become a viable and competitive platform for future GaN electronic devices.

ED-Thu-B7* - 805 V Breakdown Voltage, 3.5 mΩcm² specific Ron, GaN-on-Si Pseudo-Vertical p-n diode grown by localized epitaxy

4. Electronic devices

David Plaza Arguello[1]
Mohammed El Amrami[1], Zakariae M'Qaddem[1], Hala El Rammouz[1], Thomas Kaltsounis[1], Matthieu Lafossas[1], Simona Torrengo[1], Julien Buckley[1], Matthew Charles[1]
[1] CEA Leti, Université Grenoble Alpes, Grenoble, France

Abstract text: Gallium Nitride (GaN) has drawn significant interest in power electronics due to its exceptional electron mobility, high saturation velocity, and critical electric field. However, limited availability and high cost of free-standing (FS) GaN substrates hinder adoption. Silicon is a cost-effective alternative substrate, but lattice and thermal coefficient mismatch with GaN generate dislocations and large tensile strain in GaN layers. Achieving the full potential of GaN on silicon requires both successful epitaxial growth and improved device processing.

Localized epitaxial growth can mitigate these challenges by improving material quality and enabling innovative device architectures. This study investigates how epitaxy-related limitations affect the electrical performance of pseudo-vertical GaN-on-Si p-n diodes, achieving high breakdown voltage (BV) and low specific Ron ($R_{on,sp}$) with 100 µm diameter diodes. By refining processing steps and adapting to the challenges from epitaxy, we aim to improve breakdown voltage and reduce leakage currents on cost-effective GaN-on-Si power devices.

In this work, localized growth was performed by Metal Organic Vapor Phase Epitaxy (MOVPE) on 200 mm GaN on Si (111) template wafers patterned with a 50 nm Al_2O_3 mask. The layers consisted of a 10 µm-thick Si-doped n-GaN drift layer (~1-2×10^{16} cm^{-3}) and a 700 nm p-GaN layer (~5×10^{18} cm^{-3} Mg doping), forming the p-n junction. The wafers were diced into squares, and then pseudo vertical diodes were fabricated with a Ni/Au (50/150 nm) anode on the top surface and a Ti/Al/Ni/Au (95/200/20/265 nm) cathode on the lower part after etching the Al_2O_3 mask.

Hexagonal mesas 100 µm and 200 µm in diameter were analyzed. Under reverse bias, many devices demonstrated BV above 700 V, with a threshold voltage of ~3 V under forward bias for both device sizes. Larger mesas suffer degraded and less consistent performance, significantly increasing $R_{on,sp}$. FIB-SEM analysis showed that this was due to crack formation below the mesas due to the strain in the GaN layers. In contrast, the 100 µm devices, where cracking is less severe or non-existent, show excellent performance, with BV up to 805 V and $R_{on,sp}$ of 3.5 mΩcm² at 10 V. These results confirm the potential of localized epitaxy for GaN-on-Si power devices.

ED-Thu-B8 - Electrical properties of fully vertical AlGaN/SiC p–n diodes at specific Al compositions to reduce the hetero interfacial potential barrier

4. Electronic devices

Yoshinao Miura[1]
Hisashi Yamada[1], Hirohisa Hirai[1], Akira Nakajima[1], Kazutoshi Kojima[1], Shinsuke Harada[1]
[1] National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan

Abstract text: We investigated fully vertical AlGaN diodes on SiC substrates with low resistivity and high-thermal conductivity, to realize next-generation power devices using ultrawide-gap AlGaN alloys (3.4-6.2 eV). Previously, we successfully obtained fully relaxed and crack-free AlGaN epitaxial layers grown directly on SiC substrates using MOCVD [1]. The fabricated AlGaN/SiC SBDs exhibited excellent rectification characteristics [2]. We also noted that the Al composition at the hetero interface is critically important for reducing the potential barrier caused by the band discontinuities. In this paper, we present the electrical properties of fabricated AlGaN PNDs with specific Al compositions around 30 % (x=0.3) at the interface.

The epitaxial AlGaN layers for the PNDs were grown on the on-axis Si-face n^+-SiC (0001) using MOCVD. The stacked epitaxial structure was p^+-GaN (~1E20 cm^{-3}, 20 nm) / p-AlGaN distributed polarization doped (DPD) (x=0.0-0.3, [Mg]~3E19 cm^{-3}, 70 nm) / n-AlGaN (x=0.3, [Si]~3E17 cm^{-3}, 950 nm) / n^+-AlGaN (x=0.3, [Si]~5E18 cm^{-3}, 50 nm). Magnesium doping in the p-DPD layer was performed to ensure a one-sided abrupt p-n junction. RSM-XRD analysis revealed that the p^+-GaN and p-DPD-AlGaN layers grew pseudo morphically on the fully relaxed n-AlGaN layer. The surface of p^+-GaN showed a crack-free and smooth morphology. The p–n diode was defined with a vertical mesa structure that reaches the SiC substrate.

Typical $1/C^2$–V plots of the fabricated PNDs exhibited linear characteristics with an extrapolated built-in potential of 4.8 V, which was near the expected value (~4 V) for the AlGaN junction (x= 0.3). The forward J–V characteristics demonstrated good rectification with an on/off ratio of >1E9. The differential resistance R_{diff} of 1.2 $m\Omega \cdot cm^2$ at V_F = 8V indicated that the parasitic resistance of the AlGaN/SiC hetero interface could be reduced substantially. Regarding the reverse J–V characteristics, the observed maximum breakdown voltage of 210 V corresponds to a breakdown field of 3.9 MV/cm, which is higher than that of GaN. The electrical properties of the present p–n diodes are promising for the realization of fully vertical AlGaN/SiC power devices.

This study was supported by the Innovative Science and Technology Initiative for Security, (Grant Number JPJ004596, ATLA, Japan).

[1] H. Yamada et al., IWUMD2024. [2] Y. Miura et al., IWN2024.

ED-Thu-B9* - 1.5 kV Fully-Vertical GaN-on-Si Power MOSFETs

4. Electronic devices

Yuchuan Ma[1]
Shuhui Zhang[1], Hang Chen[1], Xiangyu Teng[1], Xiaoping Meng[1], Huantao Duan[2], Bin Hu[2], Huimei Ma[2], Jianfei Shen[2], Minghua Zhu[2], Jin Rao[2], **Chao Liu**[1]
[1] School of Integrated Circuits, Shandong University, Jinan 250100, China
[2] Huawei Technologies Co., Ltd. Huawei Base, Bantian, Longgang district Shenzhen, Guangdong 518129, China

Abstract text: We report 1.5 kV fully-vertical GaN-on-Si trench MOSFETs (FV-MOS) leveraging conductive buffer layers and fluorine-implanted termination (FIT). By integrating a conductive buffer, the low-resistance Si substrate inherently functions as the drain electrode, eliminating the n-GaN drain layer, breaking the strain constraints, and enabling the growth of a 7 μm thick drift layer on 6-inch Si substrates. Fluorine ion implantation is employed to convert the peripheral n^+-GaN/p-GaN layers into highly resistive regions, enabling effective device isolation and mitigating electric field crowding at mesa etching termination (MET) edges. The fabricated FIT-FV-MOS exhibits a record breakdown voltage of 1495 V, combined with a threshold voltage of 4.2 V, a specific on-resistance of 9.7 mΩ·cm², and an on/off ratio of ~10^7. The device development progressed through three phases. Firstly, low-leakage quasi-vertical GaN-on-Si trench MOSFETs (QV-MOS, Fig. 1(a)) were fabricated. Secondly, the conductive buffer strategy enabled fully vertical MET-FV-MOS devices (Fig. 1(b)) with a 7 μm GaN drift layer, as strain limitations were resolved by omitting the n-GaN drain layer. Finally, the FIT structure (Fig. 1(c)) replaced traditional MET to address electric field crowding, yielding FIT-FV-MOS with a record 1495 V breakdown voltage. All devices share a uniform gate stack with a 100 nm conformal SiO_2 dielectric layer (Fig. 1(d)). Fig. 2(a)-(f) depict the cross-sectional SEM images and SIMS profiles of the N-P-N epitaxial structures for the fabricated vertical MOSFETs. Fig. 3, Fig. 4, and Fig. 5 present the device results of the fabricated QV-MOS, MET-FV-MOS, and FIT-FV-MOS, respectively. Figure 6(a) compares the specific on-resistance and breakdown voltage of the fabricated devices with previously reported vertical GaN trench MOSFETs. To ensure rigorous comparison, BV values for all devices in this work and prior studies are defined at a leakage current density of 1 mA/cm², as illustrated in Fig. 6(b). Remarkably, the fabricated GaN-on-Si trench MOSFETs demonstrate BV levels comparable to GaN-on-GaN counterparts and superior to the vertical GaN MOSFETs on foreign substrates (Si or sapphire). These advancements highlight the feasibility of cost-efficient vertical GaN-on-Si transistors for kV-class applications such as EV powertrains and grid-scale renewable energy converters.

ED-Thu-B10* - Anomalous Output Characteristics in GaN Vertical Trench MOSFETs under Large Drain Voltage

4. Electronic devices

Nami Kusunoki[1]
Yuki Ichikawa[1], Tohru Oka[2], Nariaki Tanaka[3], Kazuya Hasegawa[3], Takatomi Izumi[3], Takaki Niwa[3], Suda Jun[4]
[1] Nagoya University, Nagoya, Aichi, Japan
[2] Nagoya University, Nagoya, Aichi, Japan; Toyoda Gosei, Ama, Aichi, Japan
[3] Toyoda Gosei, Ama, Aichi, Japan
[4] IMaSS, Nagoya University, Nagoya, Aichi, Japan

Abstract text: GaN vertical trench MOSFETs have attracted much attention as next-generation power devices due to their low on-resistance and high breakdown voltage. However, reliability challenges remain, such as threshold voltage shifts under gate bias stress [1]. In this study, we focus on the output characteristics, which are important for power electronics applications. We observed unusual short-channel-effect-like behavior at large drain voltages (V_{DS} > 2 V). Notably, we found that sub-band-gap light illumination effectively suppresses these anomalies.

The MOSFET structure used in this study was identical to that in our previous report [2], except for the Mg concentration and p-body thickness, which were set at 6×10^{18} cm^{-3} and 0.3 μm, respectively. The I_D-V_{DS} characteristics within a sweep range of 0–2 V exhibited normal output behavior, with a slight increase in I_D in the saturation region. However, when extending the sweep range to 0–10 V, anomalous behavior emerged, characterized by a significant increase in I_D with increasing V_{DS}. Additionally, dual-sweep measurements revealed large hysteresis, where I_D in the backward sweep was significantly lower than in the forward sweep, indicating that the observed phenomenon cannot be solely attributed to the short-channel effect.

To further investigate this behavior, we examined output characteristics under sub-E_g light illumination at various wavelengths. Under 405 nm LED illumination, the output characteristics improved to an ideal one, with clear I_D saturation and complete hysteresis suppression. Under 470 nm LED illumination, the unusual behavior was observed in fast-sweep-speed measurements but was mitigated with reducing sweep speed. These experimental results suggest that the recovery of output characteristics is driven by the response of Mg acceptors, trap states or p-body contact to LED illumination.

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Alloy disorder

2025-07-10
10:30 - 12:00
Alloy disorder

PC-Thu-6 - Disorder and the luminescence of InGaN emitters

2. Physics and characterization

Aurelien David[1]
[1] Google / Raxium, Fremont CA, USA

Abstract text: It is now well accepted that III-Nitride quantum wells display random alloy disorder, which localizes low-energy quantum states. However, the practical implications of this effect remain controversial, due to difficulties in probing localization experimentally and in modeling it accurately.

This talk will present an in-depth analysis of the effect of disorder on the optical properties of InGaN emitters, comparing theory and experiment. We will show how disorder underlies several outstanding experimental signatures: the luminescence lineshape (including its complex dependence on temperature and carrier density); the Stokes shift; the carrier temperature; and the effect of quantum well design. We will also discuss implications for the peculiar properties of next-generation emitters, such as red InGaN LEDs.

PC-Thu-7* - Multimicroscopy study of charge carrier dynamics in highly uniform (In,Ga)N layers

2. Physics and characterization

Aidan Campbell[1]
Jingxuan Kang[1], Lutz Geelhaar[1], Oliver Brandt[1], Jonas Lähnemann[1]
[1] Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V, Berlin, Deutschland

Abstract text: Improvements in the spatial and temporal resolutions of time-resolved (TR-) cathodoluminescence (CL) spectroscopy in a scanning electron microscope (SEM) provide the opportunity to study in greater detail charge carrier dynamics in ternary alloys. These and the correlation with other analytical SEM techniques allow to evaluate effects which crucially affect the $In_xGa_{1-x}N$ device efficiency such as the role of lateral alloy variations and non-radiative threading dislocations (TDs). Existing literature has limited work on layers in the order of several hundred nm thickness due to growth challenges. We recently demonstrated the achievement of layers with a TD density of 1×10^9 cm^{-2} and a local lateral alloy homogeneity probed by emission mapping of $\Delta x = \pm 0.008$ for $x = 0.12$ [1]. These layers are obtained by plasma-assisted molecular beam epitaxy (MBE) for thicknesses of 400–800 nm, across the range $0.07 \leq x \leq 0.13$.

In this work, spatial mapping of CL decay transients around TDs demonstrates reduced carrier lifetimes as a function of distance from such TDs. The extent of this effect is seen to vary between TDs of the same CL intensity contrast, alluding to a varying impact of TD types and point defect clustering on the carrier lifetimes. CL peak emission maps reveal an unreported blueshift in the outcrop of some TDs, which may act as a potential barrier to reduce non-radiative recombination. To map lateral alloy fluctuations, energy dispersive X-ray spectroscopy (EDX) has been correlated to the CL emission energy, where we observe In content gradients across a ‘mound’ morphology, characteristic to MBE growth of GaN and its alloys. Such a distribution of In is explained by the compositional pulling effect for strain gradients across the mounds, which is evidenced by cross-correlated high-resolution electron backscattered diffraction (HR-EBSD). By correlation of these techniques, the influence of these strain and In gradients on both carrier localisation and defect formation is investigated.

This work establishes a multimicroscopy methodology for future correlative studies of nanoscale strain variations, alloy homogeneity, and carrier dynamics, with particular relevance in characterising $In_xGa_{1-x}N$ pseudo-substrates, which have gained attention in applications for micro LEDs emitting in the red spectral range.

[1] Kang *et al.* 2025 *J. Phys. D: Appl. Phys.* 58, 14LT01

PC-Thu-8* - Occurrence of hot carrier emission in photoluminescence spectra of wide blue InGaN quantum wells grown by molecular beam epitaxy

2. Physics and characterization

Conny Becht[1]
Lukas Uhlig[1], Ulrich T. Schwarz[1], Mateusz Hajdel[2], Grzegorz Muziol[2]
[1] Institute of Physics, Chemnitz University of Technology, Chemnitz, Germany
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: Wide (> 5 nm) InGaN quantum wells (QW) are potential candidates in overcoming the efficiency drop at large carrier densities [1]. These heterostructures show interesting physics, e.g. the presence of dark carriers within the QW [2] or a smooth transition from quantum confinement to bulk-like behavior [3]. Here, we report the direct observation of band-to-band recombination of hot carriers, which is possible because of the dark state nature of the ground state band-to-band transition.
The analysis is done with a confocal microscope, in particular micro-electroluminescence (μEL) and micro-photoluminescence (μPL). Several single QWs grown by molecular beam epitaxy (MBE) are studied where the QW thickness varies between 2.6 and 25 nm. Spectra are recorded at different injection densities and temperatures (10 K to room temperature). A simulation is computed to compare theoretical expected emission with the experimental obtained ones.
The 2.6 nm QW shows the typical blue shift of the peak emission when charge carrier density increases due to quantum confined Stark effect (QCSE) and band-filling [4]. The 7.8 and 25 nm QW show for PL and EL at lowest carrier injection densities a luminescence peak at transition energies higher than the near-band edge (NBE) QW emission peak that is attributed to the hot carrier emission. Simultaneously the NBE QW emission peak cannot be observed or is very weak in intensity. This is explained by the poor wavefunction overlap of ground state carriers.
The line shape of the observed hot carrier emission can be quantitatively explained by k.p simulations of the spontaneous radiative recombination with the assumption that all hot carrier states have equal occupation and that only states in k-space within a certain radius are contributing to the spectrum. The first assumption corresponds to a flow equilibrium of carriers during carrier capture, the second to predominate scattering with phonon emission.
In summary, we report an experimental observation of a direct band-to-band recombination of hot carriers within blue InGaN wide QWs.

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PC-Thu-9 - Strain-free growth and structural evolution of (Al,Sc)N nanowires: New insights into composition-dependent alloy fluctuations

2. Physics and characterization

Adriano Notarangelo[1]
Hans Tornatzky[1], Aidan F. Campbell[1], Ileana Florea[2], Philippe Vennéguès[2], Jonas Lähnemann[1], Achim Trampert[1], Thomas Auzelle[1], Lutz Geelhaar[1], Oliver Brandt[1], **Philipp M. John**[1]
[1] Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V.
[2] Université Côte d'Azur, CRHEA, CNRS, 06905 Sophia-Antipolis Cedex, France

Abstract text: Alloying hexagonal wurtzite group III-nitrides with cubic rock-salt transition metal nitrides leads to new ternary compounds with exciting properties. The archetypical example is wurtzite $Al_{1-x}Sc_xN$, which has a piezoelectric coefficient up to five times higher than binary AlN and exhibits ferroelectricity. Such new functionalities emerge from lattice distortions caused by the substitution of tetrahedrally coordinated Al atoms by Sc, preferentially adopting an octahedral coordination. The result is a metastable alloy exhibiting an anomalous evolution of lattice parameters and bond angles as a function of Sc concentration. However, the absence of strain-free material across a large compositional range makes it challenging to understand the nonlinear properties of $Al_{1-x}Sc_xN$, despite their critical role in applications.

In this contribution, we use molecular beam epitaxy to grow $Al_{1-x}Sc_xN$ with $0 \leq x \leq 0.38$ on self-assembled AlN nanowire stems on sputtered TiN substrates. The nanowire geometry allows elastic relaxation to occur, resulting in strain-free $Al_{1-x}Sc_xN$. At high substrate temperatures (> 800 °C), a phase separation of the ternary $Al_{1-x}Sc_xN$ is observed, accompanied by nanowire branching and Raman signals characteristic for cubic rock-salt ScN. In contrast, moderate substrate temperatures well below 700 °C favor the formation of wurtzite $Al_{1-x}Sc_xN$ nanowires with a morphology characterized by inverse nanowire tapering. Our wurtzite $Al_{1-x}Sc_xN$ nanowires show first an increase and then a decrease in the *c*-lattice constant as a function of Sc concentration, with a maximum around x = 0.2, in agreement with *ab-initio* calculations and previous experimental studies. More importantly, a continuous broadening of the longitudinal $Al_{1-x}Sc_xN(0002)$ reflection is observed by x-ray diffraction. Since strong compositional gradients and wire-to-wire inhomogeneities are excluded by scanning transmission electron microscopy, alloy fluctuations on the microscopic scale, including Sc clustering, remain as only plausible reason. The E_2^{high} and $A_1(TO)$ Raman modes of AlN are broadened upon Sc-incorporation, confirming the strong disorder in $Al_{1-x}Sc_xN$. Their continuous red-shift observed as a function of Sc concentration evidences its enhanced incorporation into the wurtzite lattice and is explained by a change of atomic mass, bond angles and softening of the anion-cation bonds.

PC-Thu-10* - Influence of alloy disorder effects on the anisotropy of emission diagrams in AlxGa1-xN alloys, quantum wells and multiple quantum wells

2. Physics and characterization

Alexandra Ibanez[1]
Nikita Nikitskiy[2], Wilfried Desrat[1], Pierre Valvin[1], Fumiya Chugenji[3], Kirihara Taiga[3], M. Ajmal Khan[3], Hideki Hirayama[3], Guillaume Cassabois[1], Mathieu Leroux[2], Julien Brault[2], Bernard Gil[1]
[1] UMR 5221, Laboratoire Charles Coulomb and Université Montpellier, Montpellier, 34095, FRANCE
[2] CNRS-CRHEA, Université Côte d'Azur, Valbonne, 06560, FRANCE
[3] RIKEN Cluster for Pioneering Research (CPR), 2-1 Hirosawa, Wako, Saitama 351-0198, JAPAN

Abstract text: Ultra-wide and direct band gap aluminum gallium nitride ($Al_xGa_{1-x}N$) materials are attracting increasingly more interest in photonics and electronics, for instance to realize power transistors or UV light emitting diodes. To fully exploit their potential, it is necessary to determine their physical properties, in particular, their optical characteristics.

The purpose of the present work is to address a study of the optical properties of a wide series of $Al_xGa_{1-x}N$ based heterostructures emitting from 310nm down to 209nm. Photoluminescence (PL) were performed on thick epilayers grown by metal organic vapour phase epitaxy as well as single quantum wells (QWs) grown by molecular beam epitaxy on AlN templates [1] and multiple quantum wells (MQWs) grown by metal-organic chemical vapor deposition. The full width at half maximum of the PL and the orientations and shapes of the on-side emission diagrams are interpreted in terms of: 1) a fluctuation of the QWs thickness ; 2) a fluctuation of the $Al_xGa_{1-x}N$ composition leading to variations of the Quantum Confined Stark Effect; 3) a distribution of the $Al_xGa_{1-x}N$ composition simultaneously causing: i) the localization of carriers to deep composition-dependent fluctuations of the energy landscape and ii) a maximum of the built-in strain-induced intra-valence-band mixings. In particular, the strength of the alloy broadening is shown to significantly contribute to the isotropy of the light emission when the Aluminium composition reaches the 50-70% region, i.e. for an emission wavelength in the 240-270nm range. Such a property explains the substantial proportion of light emission polarized in the growth plane [2].

This work was supported by ANR funding GANEX (ANR-11-LABX-0014) and DOPALGAN <ANR-22-CE51-0035>.

References

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AlN and Al ternaries for devices

2025-07-10
13:30 - 15:00
AlN and Al ternaries for devices

GR-Thu-11 - Deep-UV LEDs Fabricated on Face-to-Face Annealed Sputter-Deposited AlN Templates

1. Growth

Hideto Miyake[1]
Ryota Akaike[1], Hiroki Yasunaga[1], Takao Nakamura[1]
[1] Mie University, Tsu 514-8507, Japan

Abstract text: To fabricate deep-ultraviolet(DUV)-LEDs with high efficiency, the crystallinity of AlGaN must be improved, and is significantly influenced by that of the underlying AlN template. The face-to-face annealed sputter-deposited AlN templates (FFA Sp-AlN) have achieved one order of magnitude lower threading dislocation densities (TDDs) than those of typical MOVPE-grown AlN on sapphire substrates [1]. Furthermore, sputter deposition and high-temperature annealing are simple and cost-effective processes compared with MOVPE. In this presentation, we will demonstrate recent progress in the quality improvement of FFA Sp-AlN and UV-C LEDs fabricated on FFA Sp-AlN.

Reducing TDDs in FFA Sp-AlN and achieving surface flattening of AlGaN grown on FFA Sp-AlN are crucial for obtaining a high external quantum efficiency (EQE). The TDDs in FFA Sp-AlN decrease with increasing AlN film thickness and annealing temperature [2]. Additionally, we adopted the thermal cycle annealing (TCA) method [3]. With a sputtering temperature of 750°C, a thickness of 450-600 nm, and subsequent TCA at 1600–1700°C for 18-44 h, we achieved FFA Sp-AlN templates with screw and total TDDs in the range of TDDs of 10^3-10^4 and 10^7 cm^{-2}, respectively. To suppress spiral growth, MOVPE growth conditions were carefully optimized, leading to the realization of a 1-μm-thick $Al_{0.75}Ga_{0.25}N$ layer with a smooth surface.

The electroluminescence spectrum and *I–L* characteristics of the UV-C LEDs were characterized at room temperature under continuous-wave current injection. After encapsulation with a silicone-based UV-transparent resin, a maximum EQE of 8.0% and an output power of 6.6 mW at a 20-mA injection current were achieved, with a peak emission wavelength of 263 nm. For a 1000×1000 $μm^2$ chip, a maximum EQE of 5.2% and an output power of 107 mW at an injection current of 500 mA were obtained [4]. Furthermore, the EQE of far-UVC LEDs with low Al composition differentiation or a DH structure was enhanced to approximately 0.6% and 1.4% under continuous-wave operation at 230 nm and 236 nm, respectively [5].

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GR-Thu-12 - Magnetron sputter epitaxy of AlScN gate dielectric on AlGaN/GaN high electron mobility transistors

1. Growth

Rachid Driad[1]
Ali Yassine[2], Akash Nair[1], Heiko Czap[1], Stefan Müller[1], Lutz Kirste[1], Mohamed Yassine[2], Michael Mikulla[1]
[1] Fraunhofer - IAF, Freiburg, Germany
[2] Inatech, Albert-Ludwigs University, Freiburg, Germany

Abstract text: AlScN is an attractive material for piezoelectric MEMS, HEMTs and ferroelectric devices [1]. High quality AlScN layers are typically grown by MOCVD or MBE. The latter is rather complex, slow, costly and less suitable for production. MOCVD enables volume production, but for AlScN, many challenges (vapor pressure of precursors, growth rate or interface issues) need to be overcome. Magnetron sputtering epitaxy (MSE) offers a low temperature, cost-effective and scalable approach, suitable for industrial applications.

In this work, we report the growth of AlScN on structured AlGaN/GaN HEMTs by MSE and evaluate their material and device properties. Although AlScN can be patterned by wet/dry etching, etch rates are low and selectivity is poor. In addition to reproducibility and uniformity issues, surface morphology may be affected. In this study, we opted for local MSE growth of AlScN on top of AlGaN/GaN HEMTs using a patterned oxide and a lift-off process. AlScN calibration layers were sputtered on silicon and sapphire substrates [2]. $Al_{0.70}Sc_{0.30}N$ layers with variable thickness were then deposited by MSE on top of MOCVD grown AlGaN/GaN HEMTs.

Smooth morphology and atomic steps are maintained after MSE in the AlScN-AlGaN/GaN HEMT structures. The RMS average of 10x10 μm^2 AFM scans remained below 0.7 nm. The crystalline quality and layer thicknesses were determined from HRXRD $\Theta/2\Theta$-scans in combination with XRR. HEMT devices were then manufactured on AlScN-AlGaN/GaN heterostructures.

Compared to reference structures, C–V measurements show an increase of the 2DEG sheet density and a shift of the threshold voltage in AlScN-AlGaN/GaN HEMT structures. Hysteresis-free C-V profiles indicate a high quality AlScN-AlGaN interface. The transfer characteristics exhibit also a negative V_{th} shift of ~ -7 V (25 nm AlScN). The saturation drain current is ~20 % higher, in agreement with the increase in ns. In contrast to Ref. [1], the counterclockwise ferroelectric hysteresis obtained in these devices was relatively small (voltage tuning ~0.4 V). Further investigations into factors influencing the material and device characteristics, such as impurities/defects/traps in AlScN or at the regrown interface, are on-going to further enhance the device performance.

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GR-Thu-13* - Sputter epitaxy of TixAl1-xN over the whole compositional range

1. Growth

Emine Kaynar[1]
Florian Hörich[1], Jürgen Bläsing[1], Fabian Großmann[1], Andre Strittmatter[1], Armin Dadgar[1]
[1] Institut für Physik, Otto-von-Guericke Universität Magdeburg, Magdeburg, Germany

Abstract text: Lateral high-power GaN devices occupy large wafer surface area per Watt electrical power which is severely limiting cost reduction. Vertical device geometries promise gains in terms of electrical power per area and breakdown voltage, lowering the cost per Watt. For Si substrates, typical group-III-nitride layer sequences start with highly insulating AlN and AlGaN buffer layers to avoid melt-back etching. Therefore, true-vertical devices require backside removal of substrate and insulating layer material. An attractive alternative for true-vertical device operation would be highly conductive layers instead of insulating Al(Ga)N layers. Our focus is on relaizing such highly-conducting TiN and TiAlN layers for use in epitaxy of nitride layers stacks.

We investigate epitaxy covering the whole compositional range of TiAlN by reactive sputtering using two metallic targets and both nitrogen and ammonia as nitrogen sources. In order to avoid SiN_x formation, growth starts with a Ti pre-deposition, followed by a first TiN growth from a N_2/Ar plasma. At least 40-50 nm of this first TiN are required to achieve a high crystalline quality with (111) FWHM values of 0.59 °.Thereafter, TiN sputtering proceeds with ammonia as it promotes a smoother surface morphology. Roughness values as low as 0.78 nm (rms) are achieved after ~ 200 nm TiN. The final roughness of the whole TiN stack depends on the thickness of the first TiN layer grown with nitrogen plasma.During this first stage, rougher surface morphologies are due to an increased grain size exhibiting significant larger height differences.

First experiments to grow GaN on TiN by MOVPE result in poor surface coverage of the GaN layer. We currently investigate TiAlN also in this regard as mitigation strategy to bridge the gap to GaN growth on TiN.

TiN crystallizes in a cubic lattice whereas AlN in wurtzite lattice. A structural transition (i.e. to wz-$Ti_{1-x}Al_xN$) is expected at x_{Al}>0.69 [1]. By growing on cubic TiN and wurtzite AlN and by analyzing the whole compositional range of TiAlN,we strive to identify experimentally the crucial composition. A change of the Al content is readily achieved by adjusting the plasma power at the Al and Ti targets as we did before to achieve AlGaN [2]. Structural characterization by high resolution x-ray diffraction is accompanied by atomic force microscopy to study the surface morphology.

GR-Thu-14 - Barrier–channel intermixing and 2DEG degradation in Al-rich Al(Ga)N/AlGaN HEMTs

1. Growth

Pietro Pampili[1]
Badal Mondal[1], Jayjit Mukherjee[2], David Moran[2], Stefan Schulz[1], Peter Parbrook[1]
[1] Tyndall National Institute, University College Cork, Cork T12 R5CP, Ireland
[2] James Watt School of Engineering, University of Glasgow, Glasgow, Scotland, G12 8LT United Kingdom

Abstract text: AlGaN/GaN High-Electron Mobility Transistors (HEMTs) have emerged as leading electronic devices for high-frequency and high-power density applications due to the exceptional mobility and high carrier concentration of the 2-Dimensional Electron Gas (2DEG) that forms at the heterointerface. However, they are now reaching material limits, making it difficult to keep up with industry demands for further increases of power density. A promising solution is transitioning from GaN to ultrawide-bandgap, Al-rich AlGaN alloys as channel materials, which could offer superior lateral figures of merits [1-3]. However, this requires addressing key challenges, including alloy scattering, reliable ohmic contacts, and optimization of the Metal Organic Vapour Phase Epitaxy (MOVPE) growth conditions.

In this study, we present recent advancements in understanding and mitigating the challenges associated with producing sharp interfaces in Al-rich AlGaN/AlGaN heterostructures. The growth of high-crystal-quality AlGaN via MOVPE requires elevated temperatures; however, these conditions may induce alloy intermixing between layers of different AlGaN composition, as recently reported for UVB AlGaN lasers [4]. With Al-rich AlGaN HEMTs, we observe that intermixing at the barrier–channel interface can reduce effective polarization contrast, thereby significantly degrading or even preventing the formation of the 2DEG.

Our results show that X-Ray Diffraction (XRD) and X-Ray Reflectometry (XRR) analysis can effectively assess interface sharpness and guide optimization of the growth conditions. With this approach, we demonstrate formation of 2DEG in AlN/$Al_{0.75}Ga_{0.25}N$ and $Al_{0.75}Ga_{0.25}N$/$Al_{0.55}Ga_{0.45}N$ HEMT structures, as confirmed by capacitance-voltage (CV) and contactless conductivity measurements. Specifically, we report sheet resistivities of approximately 2500 Ω/sq and 5500 Ω/sq, respectively, for the two structures investigated, while no 2DEG evidence could be found in any of the samples in which the barrier was grown at high temperatures. The observed 2DEG degradation in smeared interfaces is also confirmed by numerical simulations.

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GR-Thu-15* - AlScN/GaN multichannel structures grown by metal-organic chemical vapour deposition

1. Growth

Teresa Duarte[1]
Isabel Streicher[2], Patrik Straňák[1], Lutz Kirste[1], Mario Prescher[1], Stefano Leone[1], Rüdiger Quay[1]
[1] Fraunhofer Institute for Applied Solid State Physics (IAF), 79108 Freiburg, Germany
[2] Consiglio Nazionale delle Ricerche - Istituto per la Microelettronica e Microsistemi (CNR-IMM), Strada VIII n. 5 - Zona Industriale, 95121 Catania, Italy

Abstract text: GaN-based high-electron-mobility transistors (HEMTs) with AlGaN barriers provide high breakdown voltages, high power density, and output power at high frequencies, making them a crucial technology for a society with a growing need for high-volume data transmission and efficient energy conversion [1, 2].
Using AlScN as a barrier material can additionally enhance device performance owing to its wide bandgap and intrinsically high spontaneous polarization. This provides higher sheet charge carrier densities (N_{sh}) and lower channel resistance resulting from the increased gradient of spontaneous and piezoelectric polarization between AlScN and GaN [1, 3]. Despite the possibilities AlScN can bring, a significant decrease in the on-resistance (R_{ON}) of devices is still needed. R_{ON} can be further reduced by lowering the sheet resistance (R_{sh}), however, this is hindered by the trade-off between N_{sh} and mobility (μ) [2].
A multichannel heterostructure can circumvent this trade-off while also decreasing R_{sh}. By using AlScN as the barrier material, lattice matching with GaN is feasible, removing the limit to the number of periods. Thanks to this lattice matching, the first demonstration of an AlScN/GaN multichannel was recently reported [4].
Multichannel heterostructures with different periods were successfully grown by MOCVD for the first time. The optimal conditions for a five-period combination were a 40 nm thick GaN channel and a 5-10 nm AlScN barrier with 8% Sc content. High-growth temperature processes, like those for GaN and SiC, frequently exhibit high interfacial diffusion and are commonly observed for MOCVD-grown heterostructures. Despite this, time-of-flight secondary ion mass spectrometry (ToF-SIMS) showed only moderate atom diffusion between the layers. Furthermore, the heterostructures evidenced smooth morphologies, with surface roughness below 1 nm (10x10 μm^2 scale), and good crystalline quality. Contactless Hall-effect measurements of the multilayers showed a N_{sh} of 3.5 x 10^{13} cm^{-2}, μ above 1600 cm^2/Vs, and R_{sh} as low as 130 Ω/sq, further demonstrating the promising nature of these structures for high-power and high-frequency applications.

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Micro LEDs 1

2025-07-10
13:30 - 15:00
Micro LEDs 1

OD-Thu-11 - Quantitative analysis of leakage current in III-nitride micro-light-emitting diodes

3. Optical devices

Matthew S. Wong[1]
Tanay Tak[1], Andrea Y. Ni[2], Kent Nitta[1], Srinivas Gandrothula[1], JaeKwon Kim[3], NamGoo Cha[3], Umesh K. Mishra[2], Steven P. DenBaars[4], **James S. Speck**[1]
[1] Materials Department, University of California, Santa Barbara, 93106, California, USA
[2] Department of Electrical and Computer Engineering, University of California, Santa Barbara, 93106, California, USA
[3] Seoul Viosys, 97-11, Sandan-ro 163beon-gil, Danwon-gu, Ansan-si, Gyeonggi-do, 15429, South Korea
[4] Materials Department and Department of Electrical and Computer Engineering, University of California, Santa Barbara, 93106, California, U

Abstract text: The electrical characteristics under forward-and reverse-bias conditions of III-nitride blue and green micro-light-emitting diodes (μLEDs) are analyzed. Commercial blue (465 nm) and green (535 nm) InGaN LED epitaxial structures on planar sapphire substrates provided from Seoul Viosys were used in this study to minimize wafer non-uniformities. Planar substrates were used to minimize the light scattering from the substrate side when performing on-wafer measurements. Standard (0.1 mm^2 mesa dimensions) LEDs and μLEDs with mesa dimensions ranging from 5×5 to 100×100 μm^2 with three different sidewall treatments, namely reference with no sidewall treatments, SiO_2 ALD sidewall passivation, and 45-min KOH chemical treatment at room temperature followed by SiO_2 ALD sidewall passivation, were fabricated. A fitting model is proposed to determine the contributions of reverse leakage current and the effectiveness of sidewall treatments. Moreover, the forward-bias currents of the μLEDs are examined using the extracted ideality factor to examine the impacts of sidewall defects. The results show that sidewall treatments are highly effective for suppression of leakage currents. From the efficiency perspective, higher wall-plug efficiency (WPE) than external quantum efficiency (EQE) is observed when the operating voltage is lower than the photon voltage in both blue and green 20×20 μm^2 devices. These observations indicate that μLEDs with sidewall treatments not only improve optical performance but also further enhance the electrical performance of devices by suppressing the leakage current paths. We consider different possible origins of the sidewall leakage current and their suppression with ALD passivation or KOH chemical treatment followed by ALD passivation.

OD-Thu-12* - MicroLED array with electrically decoupled LED cells for optical neuromorphic computing

3. Optical devices

Jens Kibgies[1]
Vladislav Agluschewitsch[1], Maximilian Müller[1], Thilo Grusie[1], Gabor Fangmann[1], Robert Kraneis[1], Rany Miranti-Augustin[1], Christian Werner[2], Andreas Waag[1]
[1] Nitride Technology Center, Institute of Semiconductor Technology, TU Braunschweig, Hans-Sommer-Straße 66, 38106 Braunschweig, Germany
[2] Ostfalia University of Applied Sciences, Robert-Koch-Platz 8A, 38440 Wolfsburg, Germany

Abstract text: The development of photonic neuromorphic computing systems has garnered significant attention due to their potential to greatly enhance parallel processing, offering capabilities beyond what conventional digital architectures can achieve. In particular, such optical networks promise orders of magnitude reduction of power consumption [1]. MicroLEDs offer unique advantages for these systems as a result of their high potential for miniaturization, scaling, and efficiency [2]. Their ability to produce high resolution optical patterns and to operate at extremely high frequencies makes them ideally suited as structured light engines for optical neuromorphic network. Our approach of a mixed optical-electrical architecture requires an efficient current-to-light conversion. Therefore, the efficient radiative recombination and slow non-radiative surface recombination velocity of gallium nitride based microLEDs is key for these applications [3].

We present the development of a microLED array with 8x16 pixels, specifically designed for an optical neuromorphic computing application [4]. Electrical decoupling of the light-emitting pixels is required to reduce crosstalk between the microLEDs as far as possible. This has been achieved through the complete removal of the layer stack down to the substrate, followed by a two-layer isolation process using photoresist to fill the deep trenches. So, the effects of a pronounced 3D topology on chip processing could substantially be reduced. The process achieved a yield of 95 %, indicating the robustness of the method. Each light-emitting cell is equipped with distinct cathode and anode contacts, reducing circuit complexity and minimizing electrical crosstalk. This decoupling process effectively reduces the leakage current to below 10 pA, which is an important prerequisite for high energy-efficiency. Additionally, we investigated the correlation between the etch depth of the separating mesa grid and the electrical and optical properties. Even though this contribution is focusing on architecture, chip processing as well as optical and electrical properties of the microLED arrays, their application in a mixed optical-electrical neuromorphic network will also be shown.

References

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OD-Thu-13 - GaN-based flexible active-matrix micro-LED displays

3. Optical devices

Yimeng Sang[1]
Zhe Zhuang[2], Zuoxu Yu[3], Wangran Wu[3], Feifan Xu[4], Tao Tao[4], Rong Zhang[5], Bin Liu[4]
[1] School of Integrated Circuits, Nanjing University, Suzhou, 215163, China; School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China
[2] School of Integrated Circuits, Nanjing University, Suzhou, 215163, China
[3] School of Integrated Circuits, National ASIC System Engineering Research Center, Southeast University, Nanjing, China
[4] School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China
[5] Xiamen University, Xiamen 361005, China

Abstract text: Micro-light-emitting diodes (μLEDs) are emerging technologies as a promising technology for flexible display applications due to their high reliability, high efficiency, high brightness, and long lifetime. However, the fabrication process of flexible μLEDs remains immature, primarily due to the complexity of mass transfer process. Besides, the demand of ultrahigh-resolution displays requires thin film transistors (TFTs) with higher mobility, which remains a challenge, especially on flexible substrates.

In this work, we developed a wafer-scale, 4-inch mass transfer technique using a laser lift-off process to fabricate GaN-based flexible μLEDs. This technique enables the potential integration of RGB μLEDs on the same wafer. By comparing the optoelectronic characteristics of RGB μLEDs before and after substrate release, we observed a more pronounced blue shift in the emission wavelength of red-emitting μLEDs. This wavelength-shift is attribute to the release of higher compressive stress within the quantum well during the laser lift-off process. Moreover, the flexible μLEDs exhibited negligible fluctuation in forward voltages, peak wavelength, and FWHM, when the convex curvature radius decreased from ∞ (flat condition) down to 3 mm.

To enable active-matrix display, we also fabricated flexible 2T1C pixel circuits using InSnO (ITO) thin-film transistors (TFT) in a mass-production-compatible process. The ultra-flat surface and extremely low coefficient of thermal expansion (CTE) of the polyimide (PI) substrate contributed to excellent wafer-scale uniformity, mechanical flexibility, and bending durability. The ITO TFT demonstrated a remarkable average mobility of 39.1 $cm^2V^{-1}s^{-1}$. The fabricated 2T1C pixel circuits were capable of operating in both pulse amplitude modulation (PAM) and pulse width modulation (PWM) schemes. After evaluating their driving characteristics, we transferred the μLEDs to the pixel circuit backplane via flip-chip bonding, forming an active-matrix μLED display. The μLED pixels could be individually controlled and possibly to display different images, highlighting their potential for future flexible displays.

OD-Thu-14* - Study of carrier diffusion and potential fluctuations in InGaN/GaN quantum wells and their impact on the performance of micro-LEDs

3. Optical devices

Simon Litschgi[1]
Amélie Dussaigne[1], Quentin Durlin[1], Guillaume Veux[1], Frédéric Barbier[1], Bruno Gayral[2], Fabian Rol[1]
[1] CEA LETI, Univ. Grenoble Alpes, Grenoble, France
[2] CEA IRIG-PHELIQS, Univ. Grenoble Alpes, Grenoble, France

Abstract text: InGaN/GaN micro-light-emitting diodes (μLEDs) are a promising technology for emerging applications such as augmented reality and chip-to-chip communication. However, as the LED size decreases to the micrometer scale, efficiency significantly drops. [1] This loss is attributed to carrier diffusion within the quantum well (QW), where carriers migrate laterally toward sidewalls and recombine non-radiatively. To address this challenge and enhance InGaN/GaN μLED performance, we investigate carrier diffusion and recombination dynamics in c-plane InGaN/GaN single QW samples grown on sapphire substrates by metalorganic vapor phase epitaxy (MOVPE). Using micro-photoluminescence (μPL) spectroscopy and time-resolved μPL (TRμPL) mappings, we analyze carrier lateral transport within InGaN/GaN QWs.

Using the spatial extension of the μPL spot as a marker of carrier diffusion, we previously demonstrated that carrier diffusion strongly depends on QW thickness due to the quantum-confined Stark effect (QCSE). Additionally, we investigated the influence of carrier density and found that carrier diffusion dynamics deviate from the standard ABC model, particularly in the low-excitation regime. [2] In this regime, μPL emission appears constrained by micrometer-scale domains, likely resulting from potential fluctuations. This work aims to further explore these domains and their impact on carrier diffusion.

To investigate carrier diffusion dynamics, we perform spectrally filtered imaging of the PL spot using 10 nm-wide bandpass filters, allowing us to probe potential fluctuations by isolating specific recombination energies. Additionally, time-resolved 2D mapping of the PL spot provides direct visualization of carrier motion over time, revealing the anisotropic nature of diffusion within these domains. Lastly, we examine carrier transport near the edge of dry-etched mesa. By applying spectral decomposition of the PL, we analyze the interplay between observed domains and non-radiative recombination at the sidewalls.

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OD-Thu-15 - A Bottom-Up InGaN Technology for Ultra-High Brightness red, green, and blue MicroLEDs

3. Optical devices

Martin Berg[1]
Magnus Heurlin[1], Ibrahim Yilmaz[1], Heera Menon[1], Navya Sri Garigapati[1], Nathanael Löfström[1], Zhaoxia Bi[1], Lars Samuelson[1], Mikael T. Björk[1]
[1] Hexagem AB, Lund, Sweden

Abstract text: We present a bottom-up technology for producing dislocation-free, strain-relaxed InGaN microLEDs in the form of sub-micron scale platelets. By using platelets, the stress induced on the InGaN material grown on GaN substrates can be drastically reduced, enabling high indium-content barriers and efficient quantum wells with peak emission tunable from blue to deep red. Furthermore, platelet-based microLEDs do not suffer from plasma-induced damage that can severely degrade device efficiencies for small sub-pixel sizes.

Platelets were seeded in 0.1 μm openings with a pitch of 1 μm in a dielectric mask on GaN buffers grown on either sapphire or Si substrates. The resulting dislocation free platelets have a truncated pyramidal shape bounded by six s-planes and a top c-plane, with a base diameter of 0.8 μm and a height of 0.5 μm. The red microLED structure consists of a bottom n-type $In_{0.15}Ga_{0.85}N$ layer followed by a single $In_{0.36}Ga_{0.64}N$ quantum well and an $In_{0.10}Ga_{0.90}N$ electron blocking layer, which is sandwiched in between layers of $In_{0.15}Ga_{0.85}N$, and finally capped with a top p-type $In_{0.15}Ga_{0.85}N$ or GaN layer.

The microLEDs presented here exhibit internal quantum efficiency values up to 60%, as measured by temperature-dependent PL, for deep red emitting quantum wells, which we attribute to very high-quality InGaN material with low residual strain, no dislocations, and low surface recombination velocities. Devices were fabricated using n-type GaN buffer as a common cathode. An Al_2O_3-film was used for sidewalls passivation and a SiN_x layer was used as spacer to anode contacts of different sizes to the p-type layer, from single-platelet devices to several hundred connected in parallel. Electroluminescence shows single peak emission that exhibits quantum confined Stark effect induced blue shift, but with peak emission longer than 630 nm even up to 1000 A/cm^2. Typical full width at half maximum values are below 58 nm up to current densities of 200 A/cm^2. EQE is found to peak at 30 A/cm^2 and then fall off slowly, dropping to 94% of the peak value at 200 A/cm^2. At peak EQE the dominant wavelength is above 640 nm, and it remains above 630 nm up to 50 A/cm^2, which is well suited for wide color gamut, and ultra-high brightness displays.

Novel Electronic Devices 4 (Devices)

2025-07-10
13:30 - 15:00
Novel Electronic Devices 4 (Devices)

ED-Thu-A11 - Development of N-polar GaN HEMTs fabricated on MBE-grown epi-structures on low dislocation GaN substrate

4. Electronic devices

Elaheh Ahmadi[1]
[1] UCLA

Abstract text: N-polar GaN HEMTs have outperformed their Ga-polar counterparts, particularly in mm-wave applications. However, there are still challenges that need to be addressed before this technology can be widely adopted. These challenges include the necessity of a complex back-barrier structure to mitigate hole traps that lead to DC–RF dispersion. Additionally, the electron mobility in the channel decreases rapidly as negative gate bias is applied, which is problematic since these devices are typically biased in deep AB class for optimal drain efficiency. In this talk, I will present an overview of the progress our team has made in addressing these issues.

ED-Thu-A12* - Neutral Beam Etching: A Pathway to High-performance E-mode Recessed-Gate GaN MOSHEMTs for Power and RF Applications

4. Electronic devices

Wenbo Ye[1]
Han Gao[1], Junmin Zhou[1], Yitian Gu[1], Yudong Li[1], Haodong Jiang[1], Xuanling Zhou[1], Wenhui Xu[2], Xin Ou[2], Xinbo Zou[1]
[1] School of Information Science and Technology, ShanghaiTech University, Shanghai, China
[2] State Key Laboratory of Materials for Integrated Circuits, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai, China

Abstract text: GaN-based E-mode transistors are highly demanded for power and RF applications due to their fail-safe property and compatibility with single-polarity voltage driving circuits. Along with p-GaN gate HEMTs, GaN recessed-gate MOSHEMTs have been regarded as another promising approach for normally-off operation, featuring wide gate swing voltages and maturity of the starting AlGaN/GaN epi-layers. Inductively coupled plasma (ICP) was commonly deployed for barrier layer thinning, however, etching damage resulting from ion bombardment and ultraviolet photons tends to degrade the device's performance. Ar-based neutral beam etching (NBE) which features focused beam of inert gas ions for precise material removal shows great potential for fine control of gate foot and mitigation of plasma-induced damage. In this work, GaN recessed-gate MOSHEMTs enabled by NBE are explicitly investigated, for both power electronics and low-noise amplifier (LNA) applications. By partially recessing AlGaN barrier, MOSHEMT show V_{th} of 1.68V, large on/off current ratio of 10^9, and low gate leakage current for both positive and negative biases. The breakdown voltage of MOSHEMTs were increased from 208 V to 701 V as L_{gd} was extended from 2 µm to 10 µm. By recessing the AlGaN barrier at different depths via Ar-based NBE, the MOSHEMTs achieved V_{th} of 1.68/2.93/4.29 V, $I_{D,sat}$ of 803/661/545 mA/mm, and small R_{on} of 5.85/6.06/7.23 Ω·mm, leading to FOM of 701/640/567 MW/cm^2, respectively. Compared to other state-of-the-art recessed-gate MOSHEMTs with similar V_{th} reported in the literature, the GaN MOSHEMTs in this study demonstrated the highest $I_{D,\,sat}$ in its class and superior FOM. For LNA applications, recessed-gate MOSHEMT (L_g = 1.2 µm & V_{th} = 0.5 V) showed cut-off frequency (f_t/f_{max}) of 9.6/27.8 GHz, along with a minimum noise figure (NF_{min}) of 1.48 dB, an associated gain (G_a) of 14.43 dB, an equivalent noise resistance (R_n) of 40.2 Ω, and an input 3rd-order interception point of 10.3 dBm at 2 GHz, benefiting from mitigation of surface defects generated during etching. At 3.5 GHz, NF_{min} slightly increased to 1.95 dB. In summary, this work highlights that Ar-based NBE gate recessing offers a promising pathway to achieving high performance E-mode GaN MOSHEMTs for power conversion and LNA applications.
Ref. [1] Gao *et al*., IEEE EDL, Vol.45, Iss.6, 2024. [2] Ye *et al*., IEEE TED, Vol.72, Iss.3, 2025.

ED-Thu-A13* - Fabrication of AlGaN FinFET devices in the a-plane direction

4. Electronic devices

Adamantia Logotheti[1]
Navya Sri Garigapati[2], Pawel Prystawko[3], Izabella Grzegory[3], Vanya Darakchieva[1], Erik Lind[2]
[1] Center for III-Nitride Technology, C3NiT-Janzén, Solid State Physics and NanoLund, Lund University, 221 00 Lund, Sweden
[2] Department of Electrical and Information Technology and NanoLund, Lund University, 22 100 Lund, Sweden
[3] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, Warsaw 01-142, Poland

Abstract text: Ultra-wide bandgap materials, such as aluminum gallium nitride ($Al_xGa_{1-x}N$), are materials of high interest because they can be used in high-voltage and high-frequency applications. due to their large band gap, high critical electric field, and high electron mobility. The growth of $Al_xGa_{1-x}N$ was accomplished on an ammonothermal-GaN substrate, which gives superior layer qualities with low dislocation densities and high electron mobilities [1].

In this work, we present the fabrication and analysis of a fully vertical device with a 5 μm thick $Al_{0.025}Ga_{0.975}N$ drift layer. This is a novel fabrication and represents a significant advancement since such a process has not been previously reported. The stack of GaN-AlGaN layers was grown on an ammonothermal-GaN bulk substrate by using MOVPE technique, and the layers have an $n^+/n/n^+$-stack with a gradient AlGaN layer in between. The fin definition was accomplished using EBL lithography. Subsequently, the fin was dry-etched with ICP-RIE, and afterwards, a TMAH wet-etch was used to smoothen the side walls. For the bottom and the top spacer, we used a 100 nm ALD-grown Al_2O_3. The gate length was defined with a PR planarization technique to be around 400 nm. The gate stack consists of an ALD 1nm/10nm bilayer Al_2O_3/HfO_2 and a 60 nm W gate metal. The formation of the gate and source contacts was accomplished with a Ti/Al lift-off process.

The transistor behavior was analyzed for a single fin and four different fin widths of AlGaN FinFET. The results concern the a-plane and, for the 100 nm width, show a normally-on behavior with a threshold voltage V_T around 1.5V. Additionally, we extracted low subthreshold swings (SS) ~ 78 mV, low $R_{on,sp} \sim 0.02$ mΩ cm^2, and a 100 V breakdown voltage (V_{BV}). The results will be compared with those of GaN FinFETs, emphasizing the advantages of utilizing AlGaN.

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ED-Thu-A14 - Electrical characterization of AlGaN fully vertical FinFETs on Ammono substrate

4. Electronic devices

Navya Sri Garigapati[1]
Adamantia Logotheti[2], Byeongchan So[3], Pawel Prystawko[4], Izabella Grzegory[4], Vanya Darakchieva[3], Mikael Björk[5], Erik Lind[6]
[1] Wallenberg Initiative Materials Science for Sustainability (WISE), Lund University & Hexagem AB, Lund, Sweden
[2] Valvo car corporation, Gothenburg, Sweden and C3NiT-Janzén & Solid-state Physics & NanoLund, Lund University, Sweden.
[3] C3NiT-Janzén & Solid-state Physics & NanoLund, Lund University, Sweden.
[4] Institute of High-pressure Physics of the Polish Academy of Sciences, Warsaw, Poland
[5] Hexagem AB, Lund, Sweden
[6] Electrical and Information Technology & NanoLund & Wallenberg Initiative Materials Science for Sustainability (WISE), Lund University, Lund, Sweden

Abstract text: III-Nitride vertical FinFETs leverage AlGaN's unique properties and FinFET structure for better performance in power electronics and RF applications. AlGaN vertical devices surpass GaN in Baliga Figure of Merit due to their increase in bandgap due to higher Al content. This work compares the DC performance of fully vertical AlGaN (*a*- and *m*-plane) FinFETs with *a*-plane GaN FinFETs. Fully vertical AlGaN FinFETs are fabricated on Ammono grown n^+ GaN substrate. The epitaxial stack included the following layers: 200 nm n^+ GaN ($N_d \approx 2\times10^{18}$ cm^{-3}), 20 nm of AlGaN graded layer (0.8 to 2.5%, $N_d \approx 5\times10^{16}$ cm^{-3}), 5 µm drift n-AlGaN layer (2.5%, $N_d \approx 10^{16}$ cm^{-3}), and 300 nm n^+ GaN ($N_d \approx 1.5\times10^{19}$ cm^{-3}). The two types of FinFETs, aligned to the *a* and *m*-plane crystallographic orientations, are fabricated using a top-down approach. The fin dimensions are 100–400 nm in width (W_{fin}), 50 µm in length, and 1-2 fins. All the FETs have a gate length of 200 nm and bilayer Al_2O_3/HfO_2 (1/10 nm) as gate oxide.
In both FET types, reducing fin width increases threshold voltage, while increasing fin width increases the minimum subthreshold swing. Both types of FETs exhibit normally off behavior, with *a*-plane FETs showing a larger V_T than *m*-plane FETs, indicating more negative fixed charges at the gate oxide-*a*-plane fin interface. An increase in fin width reduces peak g_{me} and increases R_{ON}, indicating higher fin surface conduction (normalized to fin area). The g_{me} is in the range of 60 to 100 kS/cm^2 (0.13 to 0.2 mS/µm, normalized to normalized to device width) and R_{ON} of 0.036 $m\Omega.cm^2$ (18.25 Ω.mm, normalized to device width) for *a*-type of FETs with fin width of 200 nm, slightly better performing than *m*-plane FETs. The performance of these devices is compared with *a*-plane GaN FETs having the same drift layer thickness and doping, showing similar behavior, particularly in terms of threshold voltage. In the two-fin array, R_{ON} slightly decreases with increased fin separation (0.5µm to 2µm) when normalized to the active area, due to increased current spreading in the inter-fin region, making R_{ON} dominated by drift layer resistance. Split C-V measurements are used to extract peak effective mobility, μ_{eff} ranging from 300 to 1000 cm^2/Vs, regardless of fin width. Early FET's breakdown occurs around 110 V due to the lack of edge termination, which can be improved by optimizing drift layer doping.

ED-Thu-A15 - FatTrench Channel Mobility Extraction Technique for Trench MOSFETs

4. Electronic devices

Andrew Binder[1]
Jeffrey Steinfeldt[1], Kevin Reilly[1], Mihai Negoita[1], Robert Kaplar[1]
[1] Sandia National Laboratories

Abstract text: Reduction of channel resistance for MOSFETs is a key factor in improving performance for GaN or SiC vertical devices rated at 1700 V or below. A large contributing element to high channel resistance comes from low channel mobilities, which are often reported as low as 15-30 $cm^2/V \cdot s$ for SiC and up to 200 $cm^2/V \cdot s$ for GaN. A common technique for extracting mobility in SiC planar devices is to use FatFET structures which are long channel devices where the channel resistance becomes the dominant contributor to total device resistance, and hence provides an accurate method for extracting channel mobility. For trench MOSFETs, making a long channel device is not a viable option due to the channel orientation, hence it becomes challenging to find a good approach for extracting channel mobility. One method often used to extract mobility in trench devices is the transconductance method which is known to be inaccurate and underestimates channel mobility by as much as 33% due to error from additional series resistance. Another method proposed by Ji [1] removes error associated with series resistance from the substrate and drift region but incorporates a new source of error due to accumulation resistance and can result in a significant overestimation of channel mobility. We have developed a new technique which addresses the challenge of poor extraction accuracy in conventional methods by employing a 'FatTrench' structure to disassociate extraneous resistances which lead to error in extraction. The 'FatTrench' technique employs a series of lateral trench MOSFETs with increasing trench widths and is designed to minimize the contribution of series resistance and to uniquely separate accumulation resistance from channel resistance. Further, the new technique can be employed as a conventional test structure without requiring any additional or alternate fabrication steps. Mobility extraction accuracy through the new method has been benchmarked to be within 3% error as opposed to an error of 25-75% from conventional methods. We have developed an analytical model for this new technique which demonstrates a textbook-like approach to solving for channel mobility. Furthermore, this technique has been validated in TCAD to determine the limitations of this approach for realistic geometries and non-idealities seen in real devices.

[1] D. Ji *et al., IEDM*, 2018, pp. 9.4.1-9.4.4.

Vertical Power Devices 2 (Devices)

2025-07-10
13:30 - 15:00
Vertical Power Devices 2 (Devices)

ED-Thu-B11 - Demonstration of novel vertical GaN-on-Si High Electron Mobility Transistors

4. Electronic devices

Shaohua Yan[1]
Maoxiang Fu[2], Long Chen[1], Yipeng Liao[2], Shuxin Zhang[1], Liangfeng Zhao[2], Ya Xu[2], Junfeng Wu[1], Qingbo Liu[1], Lezhi Wang[1], Xiangdong Li[3], **Zilan Li**[1]
[1] Guangdong ZIENER Semiconductor Co., Ltd., Shenzhen, China
[2] Xuzhou ZIENER Semiconductor Co., Ltd., Xuzhou, China
[3] Guangzhou WBG Semiconductor Innovation Center, Xidian University, Guangzhou, China

Abstract text: This manuscript presents a novel epitaxial growth and fabrication method for fully vertical GaN high electron mobility transistors (VHEMTs). The proposed VHEMTs adopt a fin-shaped architecture with c-plane vertical sidewalls, enabling the formation of a vertically oriented 2DEG channel.

The growth process employs metalorganic chemical vapor deposition (MOCVD) on patterned silicon substrates, where precise control of growth conditions ensures the formation of high-quality GaN fins with low dislocation densities. Subsequently, an AlGaN barrier layer and a SiN_x gate dielectric layer are uniformly grown, fully encapsulating the GaN fins. This approach provides significant flexibility in epitaxial structure design, enabling the fabrication of both depletion-mode (d-mode) and enhancement-mode (e-mode) devices. Furthermore, the periodic trench structures in the substrate introduce an additional dimension of scalability, offering new opportunities for device miniaturization.

The device fabrication process involves the formation of gate electrodes along the sidewalls of the GaN fins and ohmic source contacts on the fin tops. Following complete substrate removal, a drain electrode is formed at the bottom, resulting in a fully vertical device architecture. Compared to existing vertical devices, this novel approach introduces a fundamentally new paradigm for vertical GaN device design.

Experimental results demonstrate the successful operation of both d-mode and e-mode VHEMTs. With a patterned Si trench width of 6 μm, the d-mode devices exhibit a threshold voltage of -3.5 V, an on/off current ratio of 10^7, and a minimum subthreshold swing of 110 mV/dec. The e-mode devices achieve a threshold voltage of 1 V and an on/off current ratio of 10^5. Furthermore, device performance is influenced by variations in Si trench width.

VHEMTs also have the potential to leverage the advantages of polarization super junctions (PSJs) to further break the Ron,sp-BV limit. This work establishes a novel platform for vertical GaN HEMTs, offering enhanced area efficiency, higher current density, and significant cost advantages. With a fully vertical channel design and scalable architecture, it provides a solid foundation for the advancement of next-generation GaN power devices.

ED-Thu-B12* - Vertically Stacked GaN HEMT and SBD on Double-Channel Heterostructure for Enhanced Third-Quadrant Performance

4. Electronic devices

Hongkeng Zhu[1]
Yuan Zong[1], Francesco Marcantoni[1], Hakan Cankat Gür[1], Elison Matioli[1]
[1] Power and Wide-Band-Gap Electronics Research Laboratory (POWERlab), Institute of Electrical and Micro Engineering, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Abstract text: Multi-channel heterostructures with stacked multiple two-dimensional electron gas (2DEG) channels significantly reduce the overall sheet resistance (R_{sh}) and enable multi-channel GaN high-electron-mobility transistors (HEMTs) of low ON-resistance (R_{ON}) [1]. In this work, we introduce a novel integration scheme of multiple devices on a multi-channel platform, where each 2DEG channel is designed for specific functions. By vertically stacking GaN HEMT and an anti-paralleled Schottky barrier diode (SBD) on a double-channel heterostructure, we directly address the large reverse conduction voltage (V_{RC}) issue in GaN HEMTs due to the lack of a built-in body diode, which induces significant dead-time losses for high-frequency soft-switching power applications.

Our approach exploits independent control of the top and bottom 2DEG channels by selectively forming an Ohmic contact to the top channel and a Schottky contact to the bottom channel at the source terminal. By engineering the threshold voltages of the top-channel HEMT and bottom-channel HEMT with $V_{th(bottom)} < V_{th(top)}$, the bottom channel functions as an efficient freewheeling path during reverse conduction, thereby enhancing third-quadrant performance. Transfer length method (TLM) reveals a low contact resistance of 0.25 Ω·mm to the top channel, with extracted R_{sh} of 416 Ω/□ and 468 Ω/□ for the top and bottom 2DEG, respectively. Electrical measurements show distinct transfer characteristics for the top and bottom HEMTs, while the integrated SBD exhibits a low turn-on voltage (V_{ON}) of 0.4 V. Output measurements demonstrate that, at $V_{gs} = -6$ V, the integrated device achieves an enhanced reverse conduction performance with V_{ON} of 0.46 V at −1 mA/mm and a low V_{RC} of 1.12 V at −50 mA/mm, alongside a low forward conduction R_{ON} of 8.3 Ω·mm. This marks substantial improvements over the conventional single-channel GaN HEMT with V_{ON} of 1.42 V and V_{RC} of 2.42 V.

By efficiently utilizing the device area and enabling independent channel control, our proposed architecture leverages the intrinsic advantages of multi-channel heterostructures and opens new opportunities for integrating efficient power devices.

[1] L. Nela *et al.*, “Multi-channel nanowire devices for efficient power conversion,” *Nat Electron*, Mar. 2021.

ED-Thu-B13* - Breakdown Voltage Analysis of Vertical GaN p-n Junction Diodes with Junction Termination Extension Formed by Channeled Mg Implantation

4. Electronic devices

Kazuki Kitagawa[1]
Tsutomu Uesugi[2], Masahiro Horita[1], Tetsu Kachi[2], Jun Suda[1]
[1] Nagoya University, Department of Electronics, Nagoya, Japan
[2] Nagoya University, Institute of Materials and Systems for Sustainability (IMaSS), Nagoya, Japan

Abstract text: Selective-area p-type doping via ion implantation is crucial for vertical GaN power devices. Our group demonstrated that a high p-type activation ratio can be achieved through Mg ion implantation and subsequent ultra-high-pressure annealing (UHPA) [1]. More recently, we have focused on channeled implantation of Mg, which enables the formation of deeper junctions at relatively low implantation energies [2]. In this study, we fabricated vertical GaN p-n diodes (PNDs) with junction termination extension (JTE) structures formed via channeled implantation. The acceptor activation ratio (net acceptor concentration/Mg concentration) in the implanted region was estimated by comparing the breakdown voltage (BV) of the fabricated PNDs with TCAD simulations.

To fabricate the PNDs, channeled implantations of Mg ions were conducted at four different dosages, resulting in as-implanted Mg peak concentrations ranging from 4×10^{17} to 2×10^{18} cm^{-3} into n-type GaN homoepitaxial layers (2×10^{16} cm^{-3}, 10 μm corresponding to an idealone-sided p^+-n BV of 960 V). The main p-n junction and the 90-μm-wide JTE regions were simultaneously formed by implantation. UHPA was performed at 1300 °C for 30 min under 500 MPa of N_2.

The BV of the fabricated PNDs increased from 530 V to 1174 V with increasing implantation dosage. The highest BV of 1174 V exceeded the theoretical value of 960 V. This improvement is attributed to the graded nature of the main p-n junction formed by channeled implantation, which suppresses the peak electric field at the junction, leading to a higher BV, as predicted by TCAD simulations [3]. By comparing the measured BV values with TCAD results, the acceptor activation ratio was estimated to range from 10% to 25%. Since the activation ratio remains relatively low, further optimization of the implantation and UHPA conditions is necessary. Our approach provides a quantitative evaluation of the ion implantation process and serves as a design guideline for device fabrication utilizing channeled ion implantation.

This work was supported by MEXT -Program for Creation of Innovative Core Technology for Power Electronics, Grant Number JPJ009777.

[1] H. Sakurai, *et al*., Appl. Phys. Lett. **115**, 142104 (2019).
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[3] K. Kitagawa, *et al*., IEEE Trans. Electron Devices, **71**, 5239 (2024).

ED-Thu-B14 - Estimations of acceptor concentration and fixed charge densities in the trench of vertical GaN trench MOSFETs

4. Electronic devices

Tohru Oka[1]
Jun Suda[2]
[1] Nagoya University, Nagoya, Aichi, Japan; Toyoda Gosei, Ama, Aichi, Japan
[2] Nagoya University, Nagoya, Aichi, Japan

Abstract text: Vertical GaN trench MOSFETs are promising for power-switching devices due to high-breakdown voltage and low on-state resistance. One issue with this device is that the threshold voltage (V_{th}) is lower than expected [1]. The reasons are explained by existences of fixed positive charges (Q_f) in the trench and insufficient activation of Mg in p-GaN owing to the n^+GaN layer on the top. However, it is difficult to evaluate the acceptor concentration (N_A) and, thus, the Q_f of the actual MOSFETs. In this work, we analysed the electrical characteristics of the MOSFETs and npn structures used in the MOSFETs, and successfully estimated the N_A and the Q_f values in the trench. The structure of the evaluated MOSFETs is the same in Ref. [2]. The npn structures were fabricated on the same wafers of the MOSFETs. The N_A values were estimated by analysing the measured and the simulated I-V characteristics of the npn structures. We also used the transfer characteristics (I_d-V_{gs}) of the MOSFETs for estimating the N_A and the Q_f. The Q_f values in the trench were estimated by analysing the measured and the simulated V_g dependence of C_{gd}-V_{ds} curves of the MOSFETs. The measured I-V characteristics of the npn structures exhibited an exponential increase in current followed by an abrupt increase. We confirmed through simulations that the former results from bund-to-bund tunnelling and the latter is caused by avalanche multiplication rather than punch-through effect. The estimated N_A by analysing the I-V characteristics was almost consistent with that estimated from the subthreshold slope of the I_d-V_{gs}, verifying that these estimations are reliable. In contrast, the C_{gd}-V_{ds} curves simulated by using the Q_f estimated from the V_{th} shift of the I_d-V_{gs} (Q_{f_iv}) for the trench surface were significantly different from the experimental results. We found that the Q_{f_iv} was different from the Q_f estimated from the C-V curve of the n-MOS diode fabricated on the surface of the trench bottom (Q_{fn_h}), suggesting that the Q_f for p^+GaN and/or vertical face is different from the Q_f for horizontal n-GaN face. Finally, by using the Q_{f_iv} for p^+GaN and the Q_{fn_h} for the horizontal n-GaN face, and adjusting the Q_f for the vertical n-GaN face, we were able to reproduce the experimental results in simulation.
[1] T. Oka, Jpn. J. Appl. Phys., 58, SB0805 (2019). [2] T. Oka et al., Proc. ISPSD, p. 303 (2019).

ED-Thu-B15 - Design of High-Current-Density, Unintentionally Doped Fully Vertical AlN Power Transistors

4. Electronic devices
Zhongyunshen Zhu[1]
Tomás Palacios[1]
[1] Microsystems Technology Laboratories, Massachusetts Institute of Technology, Cambridge, USA

Abstract text: AlN is an ultrawide bandgap semiconductor ideal for next-generation power devices. With a breakdown field >10 MV/cm and high electron mobility, its Baliga's figure-of-merit (BFOM) exceeds >10 times that of GaN and SiC. However, it is challenging to heavily dope AlN due to compensation effect from deep donor states, and its low electron affinity with Fermi-level pinning impedes ohmic contact formation. These issues limit high-current-density, fully vertical AlN devices.

Here, we propose a practical structure for fully vertical AlN-channel fin field-effect transistors on an n-type SiC substrate. An N-polar AlGaN/AlN heterostructure with an unintentionally doped (UID) graded AlGaN layer induces a 3D electron gas via polarization doping. This leads to increased electron concentration (n_e>10^{18} cm^{-3}) in the source access region without compromising mobility, thus reducing the on-resistance (R_{on}). A highly n-type doped $Al_{0.6}Ga_{0.4}N$ is designed to improve source contact, while an undoped/UID AlN is utilized as the channel and drift layer. The selection of SiC substrates as the drain is mainly due to 1) highly doped n-type SiC substrates are commercially available; 2) high-quality N-polar epitaxy of AlGaN/AlN on SiC has been achieved due to a small lattice mismatch.

Device-physics simulations using Sentaurus were employed to evaluate device performance with various doping levels in the AlN nucleation layer while retaining UID AlN in the channel and drift region. The band diagram simulation indicates that increasing nucleation layer doping lowers conduction band offset (E_C) in the UID AlN, though ΔE_C (~1.3 eV) remains due to the AlN/SiC interface discontinuity. The fin structure provides excellent electrostatic gate control, effectively modulating n_e in the channel. Simulated transfer and output characteristics reveal an I_{max} over 1 A/mm at V_{DS} = 20 V with UID AlN, and nucleation layer doping variations slightly affect I_D at high V_{DS}. The simulated result shows a breakdown voltage >2000 V with 1-μm-thick AlN. The BFOM benchmarking indicates that such vertical device architecture may overcome the current obstacles and push the performance of AlN-based power transistors closer to the theoretical limit.

Acknowledgment: This work is funded by the U. S. Army Research Office (ARO)/Ohio State University (OSU) under grant SPC-1000007046 | GR129057 and Wallenberg Foundation.

Single Photon Emitters and non-classical photons

2025-07-10
13:30 - 15:00
Single Photon Emitters and non-classical photons

PC-Thu-11 - Non-classical photon emission from point-like emitters in Aluminum Nitride

2. Physics and characterization

Yanzhao Guo[1]
H Bilge Yagci[1], Joseph K Cannon[1], Samuel G Bishop[1], Rachel N Clark[1], John P Hadden[1], **Anthony J Bennett**[1]
[1] Cardiff University

Abstract text: Wide bandgap semiconductors often contain defects that exhibit luminesce at room temperature. While much attention has been given to vacancy-ion complexes in diamond, such as SiV and NV-, which possess internal spin-sub-levels useful for various applications like sensing external fields, hosting spin qubits, or generating single photons, the presence of an intersystem crossing in their energy levels limits their saturated intensity. In contrast, point-like emitters in the commercially important $Al_xGa_{1-x}N$ semiconductors have received much less scrutiny, but have been found in as-grown epilayers [1] and created using ion-implantation [2]. These emitters saturate and exhibit anti-bunched emission at room temperature, which is indicative of a quantized emitter. Furthermore, it was recently shown that emitters in GaN can host single spin qubits amenable to optical detected magnetic resonance spectroscopy [3] which opens the possibility of spin-based sensors in the III-nitrides.

We have studied the emission dynamics and photon emission statistics of a class of emitters identified in commercial AlN-on-sapphire wafers at room temperature which emit near 600 nm [4]. We find the statistics of photon emission are governed by multiple dark ‘shelving states’. We present a model which reveals laser-driven depopulation of these shelving states dominates at high power. We show this effect results in a saturated photon detection rate an order of magnitude greater than a single NV- in diamond which we use as a standard-candle to calibrate our detection system, paving the way to MHz-rate quantum light sources operating at room temperature.

References

[1] S. G. Bishop *et al*, ACS Photonics 7 (7), 1636-1641 (2020)

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[4] Y. Guo *et al*, Physical Review B 110 (1), 014109 (2024).

PC-Thu-12 - Ultraviolet Emitting Color Centers in Hexagonal and Rhombohedral Boron Nitride

2. Physics and characterization

Krzysztof Korona[1]
Jakub Iwański[1], Aleksandra Dąbrowska[1], Munavvar Husain[2], Tatiana Korona[2], Johannes Binder[1], Mateusz Tokarczyk[1], Andrzej Wysmołek[1]
[1] Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland
[2] Faculty of Chemistry, University of Warsaw, Pasteura 1, 02-093 Warsaw, Poland

Abstract text: Boron nitride (BN) attracts a lot of interest since it has an sp^2-bonded structure similar to graphene and other 2D materials. Atomic layers of BN can be stacked in different orders, which leads to several polytypes. The layers can be rotated by 180º to the A' position or shifted by one or two steps to the B or C positions. The most popular BN polytypes have the following sequences: AA' (hexagonal: hBN) and ABC (rhombohedral: rBN). The rBN polytype is interesting due to its ferroelectricity and second harmonic generation. The sp^2-BN is a very efficient emitter and its luminescence spectra contain many characteristic lines, which we investigated to identify properties of different color centers in hBN and rBN.

The investigation was made on BN layers grown by Metal Organic Vapor Phase Epitaxy at temperatures from 1000ºC to 1400ºC. Triethylboron and ammonia were used as precursors. By changing growth conditions, it was possible to obtain samples with rBN or hBN polytypes. The polytype was verified by the transmission electron microscopy and by the X-ray diffraction. The photoluminescence (PL) was excited by the third or fourth harmonic of the Ti:Sapphire laser. Time-resolved PL was measured with a UV-designed streak camera.

In the PL spectra, we observe many features starting from peak at about 230 nm down to red emission, but the sharpest lines are at about 300 nm. Their zero-phonon lines (ZPL) were at significantly different positions depending on the polytype, precisely at 299.3 nm and 302.6 nm in rBN and hBN, respectively [1]. The lines were accompanied by phonon replicas with the Γ-point phonons. The longest lifetimes were about 1 ns. Other sets of lines were observed with ZPLs at 333 nm and about 380 nm and with lifetimes of 2 ns and 1.6 ns, respectively. We have found that the exact position of the latter line changes depending on polytype: it is at 382.9 nm and 386.1 nm in rBN and hBN, respectively.

The experimental results were supplemented by calculations, performed with either time-dependent density functional theory or the semiempirical approach, which can be compared with the features of the electronic spectra of defects in BN, what provides useful indications for defects' identification. The modeled defects included carbon dimers (C_BC_N), tetramers, and Si-C complexes.

[1] J. Iwański, K. P. Korona *et al*. npj 2D Mater. Appl. **8**, 72 (2024)

PC-Thu-13 - High-pressure study of ultraviolet color centers in various polytypes of boron nitride

2. Physics and characterization

Agata Kaminska[1]
Kamil Koronski[2], Maciej Poncyljusz[1], Juliette Plo[3], Alexandra Ibanez[3], Pierre Valvin[3], Jakub Iwański[4], Andrzej Wysmołek[4], Johannes Binder[4], Aleksandra K. Dąbrowska[4], Song Li[5], Anton Pershin[5], Reda Moukaouine[5], Adam Gali[5], Thomas Poirier[6], Jiahan Li[6], James H. Edgar[6], Guillaume Cassabois[3], Bernard Gil[3]
[1] Institute of Physical Sciences, Cardinal Stefan Wyszynski University, Warsaw, Poland
[2] Institute of Physics, Polish Academy of Sciences, Warsaw, Poland
[3] Laboratoire Charles Coulomb, CNRS-Université de Montpellier, Montpellier, France
[4] Faculty of Physics, University of Warsaw, Warsaw, Poland
[5] HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[6] Tim Taylor Department of Chemical Engineering, Kansas State University, Manhattan Kansas, USA

Abstract text: Layered boron nitride is one of the key two-dimensional (2D) materials, which are intensively studied both due to the abundance of novel physical phenomena and for their numerous advanced applications. It is composed of boron and nitrogen ions forming flat sp^2 covalent bonds with a honeycomb structure inside the layers and weak van der Waals bonds between the layers, creating a three-dimensional crystal with a wide indirect bandgap of ~6 eV [1]. This large bandgap accommodates numerous optically active electronic states of structural defects and impurities that are abundant in currently grown crystals and epitaxial layers. Many of them act as bright single photon sources with various photon energies from 1.5 eV to 5.5 eV or as efficient UV emitters with extreme thermal stability [2,3]. One of the brightest is the color center emitting at 4 eV, most probably originating from carbon-related defect [2,4].

The most common 2D BN is centrosymmetric hexagonal BN (hBN), but the BN atomic planes can also be arranged in non-centrosymmetric configurations like rhombohedral (rBN) or Bernal (bBN) stacking orders. Different layer stacking sequences influence the emission properties of UV color centers in the BN host: in hBN and rBN one zero-phonon line (ZPL) is observed at 4.096 eV and 4.143 eV, respectively [5], whereas in bBN two components of ZPL at 4.145 eV and 4.161 eV are present [4]. In this work, we performed high hydrostatic pressure studies of the low-temperature photoluminescence (PL) of hBN, rBN, and bBN in the 3–4 eV spectral region using the diamond anvil cell technique. The results showed that the decrease in the PL energy with pressure was less sensitive than the bandgap, and the pressure coefficients of the PL energy depend strongly on the BN polytype. Theoretical calculations of pressure dependencies of various defect levels in BN polytypes confirmed that the emission is associated with carbon dimers. Our results show that tuning the stacking sequence in various polytypes of a given crystal provides unique “fingerprints” contributing to the identification of defects in 2D materials.

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[2] Basha et al., Sci. Rep. 11, 12285 (2021).
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[5] Iwański et al., NPJ 2D Mater. Appl. **8**, 72 (2024).

PC-Thu-14* - Depth control of room temperature single-photon emitters in gallium nitride epilayers

2. Physics and characterization

Alexandros Bampis[1]
Johann Stachurski[1], Jean-François Carlin[1], Raphaël Butté[1], Nicolas Grandjean[1]
[1] Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Abstract text: Bright quantum light sources are essential building blocks for quantum communication and linear optical quantum computing. However, most existing quantum emitters require cryogenic temperatures to operate, which constitutes a bottleneck for large scale applications.

Certain radiative point defects embedded in gallium nitride (GaN) have recently been shown to emit single photons up to room temperature, spanning wide wavelength ranges in the visible [1] and around the telecom O-band [2]. These emitters exhibit sharp a zero-phonon line and their integration in circular Bragg gratings has been reported, giving rise to excellent single photon purities [3]. Due to its widespread use for solid-state lighting, GaN is an extensively studied material which gives these single photon emitters (SPEs) another advantage for future applications. Their fundamental nature, however, is yet to be determined.

This work precisely focuses on identifying the nature of these point defects. Several sample structures, grown by metalorganic vapor phase epitaxy (MOVPE), are investigated by scanning confocal optical spectroscopy and Hanbury Brown and Twiss experiments to study the resulting defect densities and their optical properties. SPEs are found in both doped and unintentionally doped GaN samples grown on *c*-plane sapphire, displaying emission wavelengths ranging from 500 nm to 950 nm and high single-photon purities, with $g^{(2)}(0)$ values as low as 0.06 at room temperature. Those emitters, naturally present in MOVPE GaN on sapphire are shown to be interface-related defects, largely preventing high coupling efficiencies to photonic structures due to their inadequate depth position. However, we demonstrate a growth sequence that produces SPEs in GaN on sapphire at any desired depth. The influence of growth conditions, impurity concentrations and strain environment on the emitter formation are discussed.

This step constitutes a first milestone towards the site-controlled production of SPEs in GaN. This capability would enable to deterministically position photonic structures around the created emitters and reach enhanced photon collection efficiency levels - an essential requirement to obtain scalable photonic devices.

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[3] M. Meunier *et al.*, *Nanophotonics* **12**, 1405 (2023)

PC-Thu-15 - High-purity Single-photon Emitters and Sub-micron Light Emitting Diodes with Group III-Nitride Semiconductors via Nanoscale Focus Pinspot Technique

2. Physics and characterization

Yong-Hoon Cho[1]

[1] Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Republic of Korea

Abstract text: GaN-based quantum dots (QDs) and defects have been regarded as room-temperature, deterministic single photon emitters with high purity and brightness. However, it is challenging to avoid unwanted emissions from adjacent areas such as wetting layers in Stranski–Krastanov mode QDs, side quantum wells in site-controlled QD grown on pyramid apex, or other high-density QDs (or defects) surrounding the target single QD (or defect), which act as background and hence degrade single photon purity and site selectivity. Meanwhile, GaN-based micro light-emitting diodes (μLEDs) have been considered as future micro-displays owing to their high stability, efficiency, and brightness. However, the realization of high pixel-density displays is difficult because of the limitation of the high-resolution pixelation technique. To overcome the above-mentioned drawbacks, we have developed a novel nanoscale quenching technique with a focused ion beam (FIB) microscope, referred to as the nanoscale focus pinspot (NFP) [1]. First, by using the NFP technique, we demonstrate a performance improvement of single photon emitters with InGaN QDs grown on GaN pyramids [1] and InGaN quantum disks grown in GaN nanowires [2]. In addition, we recently showed spatial distribution control of defects in GaN grown on patterned sapphire substrates, emitting telecom-range single photons at room temperature [3]. The samples are characterized with various optical methods including micro-photoluminescence (PL), cathodoluminescence, time-resolved PL, and second-order photon correlation. Next, a novel μLED pixelation method without masking and etching processes has been developed using the NFP technique, and we demonstrated electrically driven sub-micrometer-scale μLED pixel arrays [4]. As a result, efficient μLED pixel arrays at sub-micrometer scales (as small as 0.5 μm side length) were achieved.

References:

[1] M. Choi *et al.*, ACS Nano 15, 11317 (2021).

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Special Focus: Nitrides go Wild

2025-07-10
16:00 - 17:30
Special Focus: Nitrides go Wild

The Soft Side of Hard Materials: Ferroelectricity in Wide-Bandgap Nitrides

4. Electronic devices

Zetian Mi[1]
[1] University of Michigan, Ann Arbor

Abstract text: The incorporation of group IIIB elements, *e.g.,* Sc and Y, can transform conventional III-nitride semiconductors to be ferroelectric, with significantly enhanced electrical, dielectric, piezoelectric, and linear and nonlinear optical properties. As such, ferroelectric nitride semiconductors have garnered significant attention for a wide range of applications in high power, high frequency, and high temperature electronics, optoelectronics, ferroelectrics, acoustoelectric, and quantum photonic devices and systems. In this presentation, I will discuss some of the emerging opportunities and obstacles faced by nitride ferroelectrics in practical applications. I will also discuss potential solutions, future research directions, and the prospects for further advancements in this rapidly evolving domain.

Single photon emitter for quantum optics and communication

4. Electronic devices

Nicolas Grandjean[1]
[1] Institute of Physics , Ecole polytechnique fédérale de Lausanne (EPFL), Switzerland

Abstract text: In recent years, several single photon emitters (SPEs) have been observed in III-nitride semiconductors both in the visible and near-infrared wavelength ranges.

In this session, we will first address the state of the art, then discuss the potential origins of SPEs, and eventually draw some perspectives for their application to photonic integrated circuits and quantum communications.

Multichannel technologies for efficient GaN power devices

4. Electronic devices

Elison Matioli[1]

[1] Institute of Electrical and Micro Engineering, Ecole Polytechnique Fédérale de Lausanne (EPFL)

Abstract text: This presentation will discuss recent advancements and emerging technologies based on multichannel III-Nitride semiconductors that aim to address some of the main challenges in power electronics. We will highlight the significant improvements in device performance achieved through the use of multi-channel structures, resulting in figures of merit that far exceed current state-of-the-art. We will present novel methods to reach normally-off operation, using p-type oxides, such as LiNiO and NiO. These methods are also extended to manage the high electric fields in these structures, to significantly increase the device breakdown voltage. These emerging technologies present exciting opportunities for the future development of III-nitride electronic devices.

Re-examining the efficiency limits of visible LED

4. Electronic devices

James Speck[1]
[1] Materials Department, University of California, Santa Barbara, USA

Abstract text: In this presentation I provide a brief overview of current understanding of the efficiency limits of blue, green and longer wavelength visible nitride LEDs in the context of current density and temperature. The remarkable progress in blue (~450 nm) LEDs has resulted in exceptional efficiency at low current density but still current droop remains a major challenge - solutions are still needed to realize true volumetric injection of the active region. The realization of high wall plug efficiency green, yellow, and red LEDs is in part through significant voltage reduction through the sidewalls of V-defects. As a result, today's blue, green, yellow and red state of the art LEDs operate close to photon voltage We discuss the consequences of V-defects on current droop and thermal droop. We show that thermal droop is a consequence of thermally activated nonradiative channels and not overflow for any LED that operates at forward bias well below the built-in voltage of the junction.

Nonlinear optical and dielectric properties of novel nitride alloys

4. Electronic devices

Chris Van de Walle[1]
[1] Materials Department, University of California, Santa Barbara, USA

Abstract text: The nitride alloys that are being explored for ferroelectricity (AlScN, AlYN, and AlBN) display other intriguing properties, such as enhanced dielectric permittivity and nonlinear optical properties. These features can be attributed to their heterostructural nature, with ScN and YN preferring the rocksalt phase and BN the layered hexagonal phase, while AlN stabilizes in the wurtzite structure. Alloying AlN with these other materials induces soft phonons and phase transitions at specific concentrations, enhancing nonlinear effects and altering physical properties.

The larger dielectric permittivity enables use as a high-k material for gate dielectrics. The electro-optic response surpasses conventional materials like lithium niobate [1], and offers the prospect of ultra-compact modulators and electro-acoustic devices for high frequency (mm-wave) filters. CMOS compatibility enables back-end-of the line integration.

Using first-principles calculations, we elucidate the mechanisms driving the enhanced dielectric and electro-optic properties in solid-solution alloys and superlattice structures. Our results provide design strategies for optimizing device performance through tailored alloy composition, cation ordering, strain engineering, and heterostructure design.

Work performed in collaboration with Haochen Wang, Zekun Wu, and Sai Mu, and supported by SUPREME (SRC/DARPA), DOE, and ARO.

[1] H. Wang, S. Mu, and C. G. Van de Walle, Appl. Phys. Lett. **126**, 041901 (2025).

Nitrides for new quantum technologies

4. Electronic devices

Debdeep Jena[1]
[1] Depts. of ECE and MSE, Cornell University, Ithaca, US

Abstract text: While among friends we can agree that nitride semiconductors have "conquered" solid state lighting, are creating solid-state UV photonics, and have succeeded in RF and power electronics, good friends must make some bets on the new directions nitrides will go in the future. While our community is working hard to ensure the success of established science and applications of the nitrides, it is exciting to think of whole nitride world that is waiting to be explored and create new applications. I will present some of my thoughts on nitride ferroelectric and nitride superconductor materials, and how their integration with nitride semiconductors is a path towards exciting new device technologies in the future ranging from memories, new acoustoelectric devices, and quantum computing.

http://djena.engineering.cornell.edu/

MicroLEDs 2

2025-07-10
16:00 - 17:30
MicroLEDs 2

OD-Thu-16 - Tantium MicroLED: Enabling Scalable, High-Efficiency Solutions for Emerging Displays

3. Optical devices

Ying-Tsang (Falcon) Liu[1]
Kuan-Yung Liao[1], Ching-Liang Lin[1], Sheng-Yuan Sun[1], Yun-Li Li[1]
[1] PlayNitride Inc.

Abstract text: MicroLED technology stands out as a leading solution for next-generation displays, delivering high pixel density, exceptional brightness, superior reliability, and strong environmental adaptability. However, power efficiency remains a major challenge, particularly in LTPS-TFT-driven MicroLED displays, where the high impedance of LTPS-TFTs leads to significant power dissipation and thermal buildup, ultimately limiting performance and lifespan.

To address these limitations, we have developed Tantium MicroLED — a novel architecture that significantly enhances current efficiency and reduces power loss. Utilizing an advanced internal tandem structure, Tantium MicroLED improves current efficiency (cd/A) while maintaining full compatibility with existing display architectures. This innovation optimizes current distribution, minimizes thermal generation, and boosts overall panel performance.

Experimental results demonstrate that at a driving current of 10 μA, Tantium MicroLED achieves 1.95x, 2.35x, and 2.1x improvements in current efficiency for red, green, and blue pixels, respectively, compared to conventional MicroLEDs. These gains are attributed to both the tandem structure and increased current density during operation. Furthermore, Tantium MicroLED maintains consistently higher efficiency across varying conditions, making it especially advantageous for high-brightness applications such as automotive displays.

When integrated with LTPS-TFT active-matrix backplanes, Tantium MicroLED panels demonstrated a 25.3% reduction in power consumption at equivalent luminance levels, corresponding to a 74.7% gain in energy efficiency over traditional MicroLED technology.

By dramatically enhancing luminous efficiency, minimizing power loss, and ensuring compatibility with existing mass transfer and TFT processes, Tantium MicroLED represents a major advancement in MicroLED display performance and paves the way for the next generation of high-efficiency, high-performance displays.

OD-Thu-17 - Progress in MOCVD Technology for Micro-LED Mass Production

2. Physics and characterization

Dominik Meyer[1]
Ian Booker[1], Adam R. Boyd[1], Michael Heuken[1]
[1] AIXTRON SE, Dornkaulstr. 2, 52134 Herzogenrath, Germany

Abstract text: Gallium Nitride (GaN) based micro-LED technology has emerged as a revolutionary advancement in the display industry, offering unparalleled brightness, efficiency, and durability. Recent developments have significantly enhanced the external quantum efficiency (EQE) of micro-LEDs, addressing previous limitations [1]. These advancements position GaN based micro-LEDs as a promising candidate for various consumer applications including smartphones and wearable devices [2]. In addition, the availability of silicon substrates with diameters up to 300 mm offers significant advantages in terms of cost-effectiveness and mass production [3].

We report recent progress of our MOCVD technology to pave the way for GaN-based micro-LED mass production on silicon substrates. Among other metrics, wafer-scale high-quality epitaxial growth with dislocation density below $5.0 \cdot 10^8$ cm^{-2} and wafer bow of below 30 µm, realized run-to-run by AIXTRON's Cl_2-assisted reactor cleaning, enable fabrication of high-performance high yield Micro-LED arrays. In addition, on-wafer emission and thickness uniformities of less than 1 nm and 0.7 %, respectively, based on an edge exclusion of not more than 3 mm for a blue micro-LED (460 nm with average FWHM of 15.5 nm) will be presented along with results extending the wavelength for green and red InGaN micro-LEDs. The influence of key growth parameters such as process temperature and pressure along with the MQW growth sequence will be reviewed.

References

[1] Bandari and Schmidt Light: Science & Applications (2024) 13:317

[2] https://www.aledia.com/en/news/the-daledia-white-paper-microled-innovation-at-the-service-of-ar-displays/

[3] https://www.infineon.com/cms/en/about-infineon/press/press-releases/2024/INFXX202409-142.html

OD-Thu-18 - Influence of the radiative lifetime on surface recombination in InGaN/GaN µ-LEDs

2. Physics and characterization

Saron Rosy De Mello[1]
Lucas Jaloustre[2], Camille Petit-Etienne[2], Erwine Pargon[2], Jean-François Carlin[3], Nicolas Grandjean[3], **Gwenole JACOPIN**[1]
[1] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France
[2] Univ. Grenoble Alpes, CNRS, CEA/LETI-Minatec, Grenoble INP, Institute of Engineering and Management University Grenoble Alpes, LTM, Grenoble F-38054, France
[3] Institute of Physics, École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Abstract text: III-nitride µ-LEDs are key candidates for micro-display applications, particularly in AR/VR systems, where pixel sizes must shrink to around 2 µm. At such scales, surface recombination becomes a dominant efficiency-limiting factor, as the pixel dimensions approach the typical carrier diffusion length in InGaN/GaN quantum wells (QW) [1]. This effect leads to significant non-radiative losses at etched sidewalls, reducing the overall efficiency of µ-LEDs.

Here, we propose to evaluate the impact of QW thickness on the carrier diffusion length, as a potential approach to reduce the influence of surface recombination. To do so, we investigated two samples grown on sapphire by MOVPE, both featuring a single $In_{0.15}Ga_{0.85}N$/GaN QW on an AlInN/GaN lattice-matched underlayer. The only difference is the QW thickness: 0.9 nm for sample A and 1.9 nm for sample B. µ-LEDs were then defined using an SiO_2 hard mask and etched by chlorine-based ICP-RIE [3]

Time-correlated cathodoluminescence spectroscopy was then used to map the local carrier lifetime with nanoscale resolution [4]. First, we found that, at the center of 2-µm LEDs, the carrier lifetime is longer for sample B (~3 ns) than sample A (~1 ns), indicating the influence of the quantum confined Stark effect. More interestingly, lifetime mapping reveals that in sample B, surface recombination affects even the center of the pixel, whereas sample A maintains a nearly constant lifetime over more than 1.5 µm.

A carrier diffusion model was finally developed to fit the experimental results. Using a consistent parameter set for both samples, we determined a carrier diffusion coefficient of D = 0.4 cm²/s and a surface recombination velocity of S = 3000 cm/s. The model estimates that the internal quantum efficiency of a 2 µm LED is reduced by ~22% for the 1 nm QW but drops by ~46% for the 2 nm QW compared to their bulk counterpart. Thus, reducing the QW thickness effectively shortens the carrier diffusion length, limiting surface recombination losses. This strategy, along with alternatives such as non-polar QWs or higher current injection, offers a path toward more efficient µ-LEDs.

[1] A. David *et al.*, Phys. Rev. Applied **15**, 054015 (2021)

[2] C. Haller *et al.*, Appl. Phys. Express **12,** 034002 (2019)

[3] L. Jaloustre *et al.*, Mater. Sci. Semicond. Process. **165**, 107654 (2023)

[4] S. Finot *et al.*, ACS Photonics **9**, 173 (2022)

OD-Thu-19* - Evaluation of the sidewall quality of InGaN micro-LEDs for different etching conditions and sidewall treatments based on cathodoluminescence behavior

2. Physics and characterization

Stefan Wolter[1]
Vladislav Agluschewitsch[1], Silke Wolter[1], Frederik Lüßmann[1], Christoph Margenfeld[1], Georg Schöttler[1], Jana Hartmann[1], Andreas Waag[1]
[1] Institute of Semiconductor Technology, TU Braunschweig, Braunschweig, Germany

Abstract text: Since InGaN/GaN micro-LEDs are promising candidates for various applications such as microdisplays, a detailed understanding of their properties as a function of size is required to optimize them. One of the most important aspects is the increasing influence of sidewall effects as the dimensions shrink. Sidewalls are known to promote non-radiative recombination and leakage currents due to inherent surface states as well as due to sidewall damage that often occurs during structuring by inductively coupled plasma (ICP) dry etching. To reduce the influence of the sidewall, its impact need to be understood in relation to the etching conditions and the consecutive sidewall treatments. In order to study this in more detail, blue InGaN/GaN micro-LEDs were defined under two different ICP dry etching conditions that differed in terms of plasma power and Ar/Cl_2 ratio, resulting in LEDs that were either stronger physically or stronger chemically ICP-etched. These LEDs were then either wet chemically etched with KOH or passivated by a SiO_x thin film deposition. In order to assess the changes in sidewall quality, the LEDs were investigated using monochromatic cathodoluminescence imaging as well as time-integrated and time-resolved cathodoluminescence spectroscopy. The stronger physically ICP-etched LEDs showed a significant reduction of cathodoluminescence intensity and decay time when excited closer towards the sidewall, consistent with the general expectation that non-radiative recombination is stronger close to the sidewall. In contrast, the luminescence properties of the stronger chemically ICP-etched LEDs were much less affected by the sidewall. The passivation of near-surface point defects by hydrogen during the etching process is discussed as a major mechanism for improving the sidewall quality. This hypothesis is supported by the observations that the cathodoluminescence signal near the sidewall can be reduced by irradiation with a low-energy electron beam or thermal annealing in an inert gas atmosphere and restored by hydrogen plasma treatment. As a consequence of the different degrees of passivation, the post-ICP treatments of the sidewall had different effects. The decay time of the stronger physically ICP-etched LEDs close to the sidewall was well recovered, while the decay time of the stronger chemically ICP-etched LEDs showed no significant change.

OD-Thu-20* - Full color emission from single InGaN-based polyhedral microstructures suitable for micro-LED displays

2. Physics and characterization

Taiki Ono[1]
Yoshinobu Matsuda[1], Mitsuru Funato[1], Yoichi Kawakami[1]
[1] Kyoto University, Kyoto, Japan

Abstract text: Micro-LED display technology is advancing rapidly for next-generation applications such as wearable glasses for augmented reality. However, conventional methods of assembling monochromatic RGB micro-LEDs from separate epitaxial wafers onto display panels face challenges in transfer yield and cost. To address these issues, monolithic integration of full-color micro-LEDs via single epitaxial growth process has gained attention. We have recently found that polyhedral GaN microstructures with multiple surface orientations formed by a resist transfer process can integrate InGaN quantum wells (QWs) with multiple emission colors. However, the color variation range is limited to a short wavelength region (violet to green). In this study, we demonstrate full-color emissions from InGaN-based polyhedral microstructures by developing growth conditions and epilayer structures.

Polyhedral GaN microstructures with a planar top (Top) and two types of slopes (Slope A and B) were patterned on a (0001) GaN template by grayscale lithography and dry etching. The etched surface was treated with wet chemical etching and chemical mechanical polishing. An InGaN QW structure optimized for red color emitters on (0001) was grown by metal-organic vapor phase epitaxy. The high In compositions for red color emissions were obtained by decreased growth temperatures and increased growth rates of the InGaN well. The emission intensity was enhanced by inserting an AlN layer above the QW and an InGaN/GaN superlattice below the QW. Additionally, the growth temperature was modulated between the InGaN well and GaN barrier.

Laser microscope measurements confirmed that Slope A and Slope B have slope angles of 2.3° and 4.4°, respectively. Room-temperature cathodoluminescence spectroscopy showed that the emission spectra from Top, Slope A, and Slope B have peak wavelengths of 627 nm, 538 nm, and 494 nm. It is noteworthy that single growth run can integrate red, green, and blue color components within a microstructure. Their plots on Commission Internationale de l'Éclairage 1931 chromaticity diagram show a wide color gamut, including white.

These results suggest a promising pathway toward efficient manufacturing of full-color micro-LED displays using a single InGaN material system.

Late News 1

2025-07-10
16:00 - 17:30
Late News 1

LN-A-1 - Characteristics of GaN HEMTs on 2-inch polycrystalline diamond substrates fabricated using the surface-activated bonding technologies

4. Electronic devices

Yosei Sunamoto[1]
Chiharu Moriyama[1], Yoshiki Nishibayashi[2], Marina Takeuchi[2], **Naoteru Shigekawa**[1], Jianbo Liang[1]
[1] Osaka Metropolitan University, Sakai, Japan
[2] Sumitomo Electric Industries, Ltd., Itami, Japan

Abstract text: GaN-based high electron mobility transistors (HEMTs) are widely used as high-power and high-frequency devices due to their excellent electron transport and capability of electrical powers. However, self-heating during operation limits their output current and reliability. To address this issue, GaN-on-diamond HEMTs that utilize diamond substrates with excellent thermal conductivity as heat spreader have garnered attention [1]. In previous works [2, 3], we transferred AlGaN/GaN/3C-SiC heterostructures grown on Si (111) substrates to a 20-mm-by-20-mm single-crystal diamond as well as a 1-inch polycrystalline diamond (PCD) substrates using the surface-activated bonding and subsequently fabricated GaN-on-diamond HEMTs. More excellent heat dissipation properties and resultant better characteristics were achieved in on-diamond HEMTs in comparison with those of on-Si or on-SiC devices. Notably HEMTs on larger diamond substrates should be realized for deploying the wafer-bonding based on-diamond devices. In this study, we fabricated GaN HEMTs on a 2-inch PCD substrate and characterized them with emphasis on their uniformity.

We measured transfer characteristics of 58 HEMTs distributed across the entire wafer for a drain bias voltage of 20 V. Their gate length and gate width were 10 and 300 μm, respectively. The maximum intrinsic transconductance of the on-PCD HEMTs was systematically larger than that of on-Si HEMTs with the same geometries. We also estimated their drain conductance (DC) in the saturation region for a gate bias voltage of 2 V. We found that the DC was negative in both types of HEMTs, and the magnitude of DC of the on-PCD HEMTs was smaller than that of DC of the on-Si HEMTs. These results imply that the wafer bonding of nitrides to PCD substrates is practically applicable to fabricate GaN-on-diamond devices with improved thermal and electrical characteristics.

Acknowledgment—This work was supported by Adaptable and Seamless Technology Transfer Program through Target-driven R&D (A-STEP) from Japan Science and Technology Agency (JST) Grant Number JPMJTR222B. Nitride heterostructures used in the work were provided by Air Water Inc.

[1] S. Hiza, et al., in Extended Abstracts of 2019 SSDM, pp. 467-468 (2019).

[2] R. Kagawa, et al., Small 2305574 (2023).

[3] C. Moriyama, et al., presented in LTB-3D 2024 (31P-14).

LN-A-2 - N-Polar High Electron Mobility Transistor (HEMT) on Silicon Substrate with Very Low Resistivity Ohmic Contacts

4. Electronic devices

Nicolas Delpuech[1]
Antoine Pedeches[2], Fabrice Semond[2], Sébastien Aroulanda[1], Mourad Oualli[1], Nicolas Michel[1], Nadia El Bondry[1], Cédric Lacam[1], Marie-Pierre Chauvat[3], Magali Morales[3], Pierre Ruterana[3]
[1] III-V Lab, 1 ave Augustin Fresnel, 91767 Palaiseau, France
[2] Université Côte d'Azur, CNRS, CRHEA, Rue Bernard Gregory, 06560 Valbonne, France
[3] CIMAP, 6. Bd. Marechal Juin, 14050 Caen, France

Abstract text: N-Polar HEMT structures are grown through NH_3 Molecular Beam Epitaxy (MBE) on a 3-inch silicon substrate at CRHEA. Growth is initiated with metal-Polar AlN buffer layer, followed by a thin (3 nm) epitaxial NbN layer and then by an N-Polar HEMT structure. Materials grown above the NbN layer are N-Polar, whereas materials below NbN are metal-Polar, as discussed in [Semond et al., Paper GR 9-6, ICNS 2023]. Based on this, we processed an N-Polar HEMT on silicon.

The top channel GaN layer is 30 nm thick. This layer was selectively removed by ICP Cl_2 etching and regrown with highly doped n+ GaN by Metalorganic Vapour Phase Epitaxy (MOVPE) at III-V Lab, following the process described in [Pitaval et al. Appl. Phys. Letters, **125**, 012108 (2024)]. MOVPE GaN n+ material grows N-Polar on the MBE template, as demonstrated by Transmission Electron Microscope (TEM) at CIMAP.

The ohmic contact is a stack of PdTiAl with a 500°C anneal as published by [Jang et al., Appl. Phys. Letters, **88**, 193505 (2006)]. However the doping of the n+ material is much higher here, close to $1x10^{20}$ cm^{-3}, resulting in very low median surface resistivities of $3x10^{-7}$ $Ohm.cm^2$. Moreover, the total measured HEMT contact linear resistivity was 0.15 Ohm.mm, consisting of contributions of 0.04 Ohm.mm for the metal to GaN n+ resistance, 0.07 Ohm.mm for the bulk GaN n+ regrown ledges and 0.04 Ohm.mm for the GaN n+ to 2D electron gas interface resistivity. The sheet resistance of the 2D electron gas is 770 Ohm/Sq.

The HEMT features a 1x100 µm wide, 250 nm long T-gate, with a NiAu gate stack and 7 nm Atomic Layer Deposition (ALD) aluminium nitride (AlN) gate insulator. The gate to source distance is 0.8 µm and the gate to drain distance is 1.5 µm. These distances do not include the 0.8 µm GaN n+ ledge on each side of the channel. The device delivers more than 1 A/mm DC drain current at 10 Volts drain voltage. The pinch-off voltage is -8 Volts. The drain and gate leakage currents are around 3 to 5 mA/mm. It is not clear yet where the relatively high leakage levels come from, on going measurements will be presented.

Acknowledgements : Agence Nationale de la Recherche (ANR) grant 2021 CE08-037 "Niobium"

LN-A-3 - Polarization interface charge model to calculate threshold voltage of AlGaN/GaN HEMTs

4. Electronic devices

Tetsuya Suemitsu[1]

[1] New Industry Creation Hatchery Center, Tohoku University, Sendai, Japan

Abstract text: Accurate estimation of the threshold voltage (V_{th}) and the sheet carrier concentration (n_s) of high electron mobility transistors (HEMTs) is crucial in advanced design of GaN-based heterostructures. We proposed a new model based on the concept that the polarization charges are distributed in an atomically thin layer beneath the surface [1] and found that the proposed model provides n_s of HEMT structures more reasonably [2]. In this work, V_{th} of HEMTs is calculated by the proposed model and compared with experimental results.

In proposed model, the polarization charges are assumed to be distributed in a thickness of δ beneath the interface. At the AlGaN/GaN interface, as a result, the sheet polarization charges in each layer is located at a distance of δ/2 from the interface. The V_{th} and n_s are obtained analytically.

First, n_s is compared with an experimental result on a HEMT structure consisting of a 15.6-nm-thick AlGaN layer with an Al composition ratio of 0.29 on a 2-μm-thick GaN layer grown on a sapphire substrate by metal organic vapor phase epitaxy. Non-destructive characterization of sheet resistance and mobility revealed 454 Ω/sq and 1530 $cm^2/V{\cdot}s$, respectively, which means n_s of 9.0 x 10^{12} cm^{-2}. The conventional model (δ=0) requires a barrier height $q\varphi_B$ of >2 eV to reproduce this n_s. The proposed model can reproduce the same n_s with more reasonable barrier height close to reported $q\varphi_B$ [3]. Next, 3-μm-gate HEMTs were fabricated using this sample and their V_{th} is characterized. The process flow is reported in [4]. The measured V_{th} of -2.2 V requires unrealistic barrier height of >2.5 eV for both conventional and proposed models. The discrepancy between measured and calculated V_{th} suggests that any process-induced damage causes a decrease in n_s and a positive shift in V_{th} in the fabricated HEMTs.

In summary, the proposed polarization model gives a nice agreement with experimental results for as-grown samples while a large discrepancy remaining in the V_{th} of fabricated HEMTs indicates a necessity of benign process developed for GaN HEMTs.

[1] T. Suemitsu, *et al.*, Phys. Status Solidi B **257**, 1900528 (2020). [2] T. Suemitsu, CSW 2024, Lund, Sweden, P16 (2024). [3] A.F.M. Anwar, *et al.*, Solid-State Electron. **50**, 1041 (2006). [4] F. Hemmi, *et al.*, Solid-State Electron. **137**, 1-5 (2017).

LN-A-4 - Gate Metal Resistance Thermometry on Fully vertical AlGaN FinFETs

4. Electronic devices

Navya Sri Garigapati[1]
Adamantia Logotheti[2], Byeongchan So[3], Pawel Prystawko[4], Izabella Grzegory[4], Vanya Darakchieva[3], Muhammad Nawaz[5], Mikael Björk[6], Erik Lind[7]
[1] Wallenberg Initiative Materials Science for Sustainability (WISE), Lund Univeristy & Hexagem AB, Lund, Sweden
[2] Volvo car corporation, Gothenburg, Sweden
[3] Center for III-Nitride Technology, C3NiT-Janzén, Solid State Physics and NanoLund, Lund University, Lund, Sweden
[4] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland
[5] Hitachi ABB Power Grids Research, Västerås, Sweden
[6] Wallenberg Initiative Materials Science for Sustainability (WISE), Hexagem AB, Lund, Sweden
[7] Center for III-Nitride Technology, C3NiT-Janzén, Electrical and Information Technology and NanoLund, Lund University, Lund, Sweden

Abstract text: AlGaN (Aluminum Gallium Nitride) is ideal for high-temperature and high-power applications due to its wide bandgap and moderate thermal conductivity. Fully vertical AlGaN devices typically offer superior heat dissipation due to their geometry, allowing heat flow through a thin drift layer, unlike the thick substrate in lateral devices. This work implements highly accurate and sensitive gate metal resistance thermometry (GMRT) on *a*-plane AlGaN single and two-fin array FETs to measure device temperature. These FETs have 5 µm thick AlGaN (2.5% Aluminum) with Silicon doping concentration of 1×10^{16}cm^{-3} on high crystalline Ammonothermal *c*-plane GaN substrates. Single-fin FETs with fin widths of 300 nm and 400 nm, as well as two-fin devices with 100 nm width and 500 nm separation, are used for measurements. All FETs have the same gate length (L_g = 200 nm) and fin length (50 µm). The Tungsten gate metal resistance is calibrated up to 150°C and the extracted thermal coefficient is 0.0018 /°C. The single-fin FET (300 nm width) shows a 26.9°C gate temperature rise at 150 mW, while the two-fin FET (100 nm width, 500 nm spacing) shows a 24.6°C rise at the same operating power. The larger device area aided slightly better heat dissipation. 3D FEM simulations in COMSOL Multiphysics were used to analyze gate metal temperature and its relation to channel temperature. The model includes a substrate with a thickness of 480 µm and thermal conductivity of 240 W/(m·K), attributed to low threading dislocation density $< 5\times10^4$ cm^{-2}. The bottom surface, representing the contact/chuck, is maintained at 25 °C to simulate backside cooling, while the top surface is subject to natural convection with a heat transfer coefficient of 5 W/(m²·K). The remaining material's thermal conductivities used here account for thickness and composition dependence. Large gate metal size causes position-dependent temperature; effective resistance is found by assuming 1D current flow along the fin length. The simulated resistance values agree well with the measured and showed that the increase in gate metal temperature, ΔT_{GM} is 50 % of the max $\Delta T_{channel}$ at a power of 125 mW for 300 nm fin width devices. Furthermore, reducing the gate metal width improves the accuracy of measuring the actual channel temperature using the GMRT method, where simulated ΔT_{GM} = 87% of the max $\Delta T_{channel}$.

LN-A-5* - Vertical GaN-on-GaN Trench MOSFETs with Enhanced ON and OFF-state Performance

4. Electronic devices
Xuancong Fan[1]
Renqiang Zhu[2], Haowen Luo[1], Kei May Lau[2], **Huaxing Jiang**[1]
[1] School of Integrated Circuits, South China University of Technology, Guangzhou, China
[2] The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China

Abstract text: Vertical GaN trench MOSFETs show considerable potential for power switching applications due to their high voltage blocking capability and excellent current handling capacity [1,2]. In the OFF-state, electric field crowding at trench corners can cause premature breakdown. This work presents an optimized trench etching profile and a thick bottom dielectric (TBD) in fully-vertical GaN-on-GaN trench MOSFETs to reduce electric field crowding and successfully increases the breakdown voltage (V_{BR}) up to 800 V.

Fig. 1 illustrates the schematic structure of the vertical GaN trench MOSFET. Device fabrication involved etching a 1.5-μm-deep trench using Ar/Cl_2 plasma with SiO_2 as the hard mask, with tuned parameters to optimize the trench profile. The trench bottom was filled with a 750-nm-thick ethylene-octene copolymer (EOC) to form the TBD layer (Fig. 2). Other fabrication processes were similar to our previous work [3]. Fig. 3 compares the transfer characteristics of trench MOSFETs with and without TBD. The MOSFET with TBD exhibits a threshold voltage of 3 V, 0.8 V higher than the device without TBD. Both devices showed comparable on/off ratios of ~10^8 and similar gate leakage currents of ~3.5×10^{-4} A/cm^2 (at V_{GS} = 15 V). Output characteristics are compared in Fig. 4. The MOSFET with TBD exhibits an $I_{DS,max}$ of 2503 A/cm^2 (at V_{GS} = 15 V, V_{DS} = 5 V) and an $R_{ON,sp}$ of 1.46 mΩ·cm^2, compared to 3027 A/cm^2 and 1.11 mΩ·cm^2 for the device without TBD. The higher $R_{ON,sp}$ in the TBD device may be attributed to the EOC covering the trench sidewalls and bottom, which hinders carrier accumulation [3]. Fig. 5 presents OFF-state leakage currents for vertical MOSFETs with and without TBD, alongside a PiN diode test structure fabricated on the same sample. The introduction of the TBD substantially enhanced the V_{BR}, increasing from 212 V to 800 V, approaching the 864 V achieved by the PiN diode. Fig. 6 benchmarks the $R_{ON,sp}$ versus V_{BR} performance of our TBD device against other reported GaN vertical trench MOSFETs. Our device achieves a competitive Baliga's Figure of Merit of 438 MW/cm^2, highlighting the potential of the TBD technique for developing high-performance and reliable GaN trench MOSFETs.

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LN-A-6 - Piezotronics effect and GaN power devices

4. Electronic devices

Weiguo Hu[1]

[1] Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, P. R. China

Abstract text: AlGaN/GaN HEMT has unique advantages on high-power and high-frequency applications owing to the high carrier concentration, high carrier mobility and large breakdown voltage. And Piezoelectric/spontaneous polarization plays a key role in two-dimensional electron gas (2DEG) formation and carrier transportation. In this work, we developed the energy band theory by coupling the constitutive equations, Poisson equation and Schrodinger equation to describe the stress-electricity-heat coupling mechanism [1]. With this model, we analyzed the spatial distribution and temporal evolution of Joule heating in power devices under current injection, which reveals the heat accumulation process and provides guidance for thermal regulation. And then, we developed the low-resistance ohmic contact process with TiAl/Au and TiAlTa/Au alloys in AlGaN/GaN HEMT. The main mechanism was attributed to the direct contact with two-dimensional electron gas (2DEG) through the substitution of the TiN compound with a smaller area Au dominated penetration. Finally, the AlGaN/GaN HEMT cantilever were fabricated by combining the anisotropic/isotropic dry etching process. This device preliminary exhibited the potential in autonomous power control due to the high power output and sensitive stress sensing [2]. These studies deepen our understanding on piezotronics, and provide a new way to optimize the performance of GaN power electronic devices. In additional, they are expected to develop new applications such as autonomous driving, bionic robot, automatic control and so on.

Keywords: GaN, MEMS, Piezotronics, neural control

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Late News 2

2025-07-10
16:00 - 17:30
Late News 2

LN-B-1* - Self-Activated Epitaxial Growth of Cubic AlScN Films from Molecular Nitrogen Without Plasma

1. Growth

Chandrashekhar Savant[1]
Rishabh Singh[2], Thai-Son Nguyen[1], Joseph Casamento[3], Huili Grace Xing[4], Debdeep Jena[4]
[1] Department of Materials Science and Engineering, Cornell university, Ithaca, NY, USA
[2] Department of Applied and Engineering Physics, Cornell university, Ithaca, NY, USA
[3] Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[4] Department of Materials Science and Engineering, School of Electrical and Computer Engineering, Kavli Institute at Cornell University for Nanoscale Science, Cornell university, Ithaca, NY, USA

Abstract text: While investigating the scavenging effect of scandium on capturing residual gas species, we discovered that crystalline semiconducting ScN could be deposited even when Sc is exposed to molecular N_2 without plasma.[1] Expanding on this novel synthesis method, we report the first demonstration of self-activated epitaxial growth of AlScN, an emerging ternary nitride with enhanced functionalities.[2,3]

N's thermodynamic preference to bond to Al over Sc and Sc's ability to self-catalyze N≡N bond breaking can facilitate AlScN growth.[4] Here, we attempt AlScN film growth using N_2, without plasma, an entirely thermal process at 550 ºC on 6H-SiC. Phase, crystal structure, epitaxial registry, and lattice parameters of films are determined. A self-activated growth of rocksalt AlScN film is observed for Al/(Al+Sc) from 0 to 47.8%. With increasing Al%, XRD 111 Bragg peak shifts and rocksalt AlScN lattice constant decreases, indicating incorporation of Al in nitrided form into AlScN films.

RHEED, XRD, & EDS spectra indicate that the cubic rocksalt AlScN films are phase pure up to 21.1% Al with N/(Al+Sc) ratio~1.1. Intermetallic Al_xSc phase separates from 28-48% Al, & N incorporation in AlScN films decreases to N/(Al+Sc)~0.5. Self-activated nitride crystal growth was not observed for films with 93-100% Al, which showed intermetallic Al_xSc & FCC α-Al phases without N. Unlike Sc, we report that Gr.III-A elements like Al, Ga, In do not facilitate N≡N breaking & thus do not grow self-activated AlN, GaN, InN films. The lattice parameters of self-activated AlScN films and Al_xSc, α-Al are reported. With increasing Al%, lattice parameter of rocksalt AlScN decreases from 4.51Å for ScN to 4.47Å for 21% Al. Self-activated AlScN films, and intermetallic Al_xSc, FCC α-Al phases, exhibit twinning and are epitaxial to substrate with their [111]/[011] || SiC[0001]/[1120].

The findings open new avenues for the ultralow-energy synthesis and processing of emerging ternary nitrides, challenging the accepted notion that high-energetic plasma assistance and use of expensive NH_3, hydrazine precursors are unavoidable. This energy-efficient processing has significant implications for advancing emerging devices.

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LN-B-2* - High mobility quaternary AlScGaN thin films grown by metalorganic chemical vapor deposition

1. Growth

Vineeta Muthuraj[1]
Claire Vozel[1], Shuji Nakamura[2], Umesh Mishra[3], Stacia Keller[3], Steven DenBaars[2]
[1] Materials Department, University of California, Santa Barbara, Santa Barbara, USA
[2] Materials and Electrical and Computer Engineering Departments, University of California, Santa Barbara, Santa Barbara, USA
[3] Electrical and Computer Engineering Department, University of California, Santa Barbara, Santa Barbara, USA

Abstract text: III-nitride HEMTs are widely used for high-power, high-frequency electronics applications. While AlGaN is the most common barrier material, increasing demand for higher power density and current-handling capability necessitates barrier materials that enable higher sheet carrier densities, such as AlScN, which also exhibits ferroelectric behavior. High-performing MOCVD-grown AlScN HEMTs have been demonstrated, but issues remain with interface roughness, unintentional Ga incorporation, and high impurity levels. These may be alleviated by growing a quaternary AlScGaN layer, which has not yet been demonstrated by MOCVD.

In this work, AlScGaN layers were deposited by MOCVD on *c*-Al_2O_3 using NH_3, TMAl, TEGa, and $(EtCp)_2Sc(dbt)$. First, a 2 µm-thick semi-insulating GaN template was using TMGa and NH_3 at a growth temperature of 1190 °C, followed by a nominally 0.7 nm thick interlayer of AlN and AlScGaN layers grown at 150 Torr at temperatures between 900 °C and 950 °C. The layer composition was modulated by adjusting the TEGa flow while holding the TMAl, $(EtCp)_2Sc(dbt)$, and NH_3 flows constant.

XRR-measured AlScGaN film thicknesses ranged from 23 to 47 nm with growth rates of 0.47 to 0.94 Å/s. XRD scans revealed Pendellösung fringes, indicating sharp interfaces between the GaN and AlScGaN. The 2DEG sheet charges from Hall measurements of heterostructures grown at 900 °C ranged from 1.4 to 3.2 x 10^{13} cm^{-2}. The highest mobility of 1731 cm^2 V^{-1} s^{-1} was from a sample with a sheet charge of 1.7 x 10^{13} cm^{-2}. The composition of this sample was $Al_{0.28}Sc_{0.05}Ga_{0.67}N$, as measured by RBS. The lowest sheet resistance of 201 Ω/□ was attained from a sample grown at 950 °C, which had a sheet charge of 2.3 x 10^{13} cm^{-2} and mobility of 1355 cm^2 V^{-1} s^{-1}, a significant improvement compared to equivalent ternary AlScN/AlN/GaN heterostructures. The effects of growth conditions on composition, surface morphology, and other film properties will be discussed. The demonstrated electron mobility of 1731 cm^2V^{-1} s^{-1} is among the highest measured for HEMT structures with sheet charges of 1.7 x 10^{13} cm^{-2} grown by MOCVD.

This work was funded in part by the Solid State Lighting and Energy Electronics Center (SSLEEC) and the Northrup Grumman GaNAMP program.

LN-B-3 - Magnetron sputter epitaxy of polar, semipolar, and nonpolar GaN thin films

1. Growth

Ching-Lien Hsiao[1]
Katrin Pingen[2], Niklas Wolff[3], Alexander Hinz[2], Per Sandström[1], Lorenz Kienle[3], Vanya Darakchieva[4]
[1] Thin Film Physics Division, Department of Physics, Chemistry, and Biology (IFM), Linköping University, Linköping,Sweden
[2] Fraunhofer Institute for Electron Beam and Plasma Technology, Dresden, Germany; Institute of Solid State Electronics, Technische Universität Dresden, Germany
[3] Department of Material Science, Kiel University, Kiel, Germany; Kiel Nano, Surface and Interface Science, Kiel University, Germany
[4] Thin Film Physics Division, Department of Physics, Chemistry, and Biology (IFM), Linköping University, Linköping,Sweden; Center for III-Nitride Technology, Lund University, Sweden

Abstract text: Magnetron sputter epitaxy (MSE) presents a promising approach for processing group-III nitride semiconductors, offering a pathway to high-quality and cost-effective GaN growth for a wide range of applications. However, the industrial adoption of MSE faces notable challenges, particularly the low growth rate associated with GaN deposition using a liquid gallium (Ga) target.

In this study, we introduce a novel UHV-compatible magnetron design with advanced cooling capabilities that enables high GaN growth rates at elevated temperatures using a solid Ga target. The system was tested over a broad range of process parameters, exhibiting stable operation while maintaining the Ga target in a solid state. Remarkably, GaN growth rates of up to 5 μm/h at room temperature and 4 μm/h at elevated temperatures were achieved—an order of magnitude improvement over MSE-grown GaN using liquid target.

The impact of Ar to N_2 partial pressure ratios and target-to-substrate distance (TSD) on growth rate, film morphology, and crystal quality was examined using scanning electron microscopy (SEM) and X-ray diffraction (XRD). Results indicate that while growth rate and morphology are sensitive to process parameters, crystal quality is also significantly influenced by film thickness. A 2 μm thick GaN film exhibited XRD rocking curve (ω-FWHM) values of 0.19° and 0.32° for the GaN (0002) and (101) reflections, respectively. Transmission electron microscopy (TEM) analysis confirmed a reduction in threading dislocation density in films thicker than 500 nm.

Furthermore, the same deposition setup was employed to grow GaN thin films on non-*c*-plane sapphire substrates. XRD and TEM characterizations revealed the successful epitaxial growth of single-crystal semipolar GaN(112) and nonpolar GaN(110) films on *m*-plane and *r*-plane sapphire, respectively. The films show anisotropic structural characteristics along the respective GaN 112 and GaN 110 out-of-plane axis resulting in ω-FWHM of the reflection along the normal that strongly depend on the azimuthal angle. Although the GaN films exhibit a small tilt with respect to the substrate surface, no rotation domains are observed by XRD or TEM investigations.

These findings underscore the potential of the MSE technique in advancing the growth of high-quality GaN thin films for applications in solid-state lighting and power electronics.

LN-B-4* - Increasing light extraction efficiency for UV LEDs with a low coverage p-GaN hole injection layer

3. Optical devices

Michael Wang[1]
Wenting Gong[1], Feng Wu[1], Tanay Tak[1], Steven DenBaars[1], Shuji Nakamura[1], James Speck[1]
[1] University of California, Santa Barbara

Abstract text: We report on the use of ultrathin low-coverage p-GaN hole injection islands on the top surface to improve the light extraction in UV LEDs, resulting in world-record UVB AlGaN UV LEDs emitting at 300 and 310 nm. With the optimization of the p-GaN island density, size, thickness, and doping, we demonstrated a 300 nm emitting device with a peak CW EQE of 18.9%, a peak CW WPE of 16.8%, and a CW EQE of 8.8% at 20 A/cm2, and a 310 nm emitting device with a peak CW EQE of 20.3%, a peak CW WPE of 15.4%, and a CW EQE of 10.9% at 20 A/cm2.

LN-B-5* - 10.4% External Quantum Efficiency 294 nm UV LEDs at 20 A/cm^2 with a Fully Transparent Tunnel Junction

3. Optical devices

Michael Wang[1]
Wenting Gong[1], Feng Wu[1], Steven DenBaars[1], Shuji Nakamura[1], James Speck[1]
[1] University of California, Santa Barbara

Abstract text: We report on the successful demonstration of an all-MOCVD grown fully transparent tunnel junction (TJ) germicidal UV LED, resulting from the use of a lightly doped n^- AlGaN contact layer enabling rapid MOCVD growth optimization. We found that the optimal condition for LED performance was a 3 nm p^{++}-$Al_{0.6}Ga_{0.4}N$ / 9 nm n^{++}-$Al_{0.65}Ga_{0.35}N$ TJ above a 20 period 1 nm p-$Al_{0.8}Ga_{0.2}N$/ 1 nm p-$Al_{0.2}Ga_{0.8}N$ short-period superlattice (SPSL). We observed a peak external quantum efficiency (EQE) of the λ = 294 nm TJ UV LED of 12.1%, and an EQE of 10.4% at 20 A/cm^2 and 9.1% at 35 A/cm^2, with an excess voltage of 1.5 V at 1 A/cm^2.

LN-B-6* - Full-color monolithic InGaN micro-LEDs with true red emission connected by tunnel junctions

3. Optical devices

Anda Cheng[1]
Lai Wang[1], You-Shiuan Chang[2], Meng-chyi Wu[2], Zhongying Zhang[3], Chihhao Chen[3], Heng Tang[3], Shaohua Huang[3], Qiangqiang Guo[1], Bo Liu[1], Zhibiao Hao[4], Changzheng Sun[4], Bing Xiong[4], Yanjun Han[1], Jian Wang[4], Hongtao Li[1], Lin Gan[4], Yi Luo[4]
[1] State Key Laboratory of Widegap Semiconductor Optoelectronic Materials and Technologies, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
[2] Institute of Electronics Engineering, Taiwan Tsing Hua University, Hsinchu 30013, Taiwan, China
[3] San'an Optoelectronics Co., Ltd. Xiamen, Fujian 361005, China
[4] Beijing National Research Center for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China

Abstract text: Boding red, green, and blue micro-LEDs to driver circuit separately known as mass transfer encounter process compatibility and efficiency degradation, especially for AlGaInP red micro-LEDs. Full-color monolithic InGaN micro-LED, which uses tunnel junctions (TJs) to stack red (R) , green (G), and blue (B) epitaxial layers, is a solution for next-generation displays due to higher pixel density and simplified processes.

MOCVD was used to grow RGB epitaxial layers and TJs throughout process. STEM analysis has confirmed the high quality of them. Employing conventional self-aligned techniques, 20×20 μm^2 full-color monolithic InGaN micro-LEDs were prepared. The electrical properties of these micro-LEDs were characterized. At an injection of 22.2 A/cm^2, the V_F for R, G, and B are 3.6 V, 4.6 V, and 4.5 V, respectively. Due to the subsequent bonding process, where the vertical height difference of the mesa cannot be too large, the thickness of the n-GaN is reduced. This results in a high V_F. The higher voltage for G is attributed to the introduction of TJs above and below. Under a reverse bias of -5 V, the leakage currents for R, G, and B are 2.2 nA, 30.2 nA, and 290.4 nA, respectively, achieving a decent level. The higher reverse leakage currents for G and B are attributed to more carrier sidewall leakage than R (strong carrier localization).

The optical properties of the RGB micro-LEDs was characterized. The peak wavelengths for G and B are 540 nm and 440 nm, with wall plug efficiency (WPE) of 8% and 10% respectively. The dominant wavelength of R is approximately 622 nm at 1 A/cm^2 and 600 nm at 100 A/cm^2, which fully meets the display even augment reality (AR) display (operating at high current density) requirements for true red color. Meanwhile, its WPE reaches 0.22% without encapsulation and backside light collection (according to experience, the WPE measured by an integrating sphere after encapsulation is about 4 times higher). This WPE for such an emission wavelength is a good result because accumulated stress would degrade the crystal quality. The color gamut of the RGB micro-LEDs exceeds the sRGB range in the CIE chromaticity diagram, demonstrating their superior application advantages in display.

In summary, full-color monolithic InGaN micro-LEDs with true red emission was demonstrated. The broad color gamut highlights its potential for micro-LED display.

Late News 3

2025-07-10
16:00 - 17:30
Late News 3

LN-C-1* - Giant polarization effects in wurtzite, zincblende, and rocksalt-based heterostructures: From theory to reality

2. Physics and characterization

Mohamed Yassine[1]
Jesus Cañas[2], Oliver Ambacher[1]
[1] University of Freiburg, Institute for sustainable systems engineering INATECH, 79110 Freiburg im Breisgau, Germany
[2] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France

Abstract text: The discovery of ferroelectricity in wurtzite (*wz*) AlScN in 2019 revealed giant spontaneous polarization values that deviated from widely accepted predictions.[1,2] This suggested the possible existence of giant polarization gradients in GaN-based structures, such as non-polar rocksalt (*rs*) ScN on strongly polar *wz*-GaN.[3] Despite this evidence, giant polarization gradients remain unobserved at *rs*-ScN/*wz*-GaN interfaces,[4] or at the well-studied zincblende-(*zb)*/*wz*-GaN-interfaces considering the long prevailing assumption that *zb*-crystals also do not own a spontaneous polarization.[5]

In this work, we were able to clarify a long-standing confusion that emerged in the nitride community between spontaneous and formal polarization and the way they are used to interpret interface charges. We resolve this confusion by tightening the definition of spontaneous polarization to ferroelectric switching, where it purely reflects a change in formal polarization between two oppositely polarized states connected by a sublattice displacement path through a defined intermediate centrosymmetric structure.[6]

Adapting this understanding to *zb*-semiconductors, we were able for the first time to identify that the intermediate centrosymmetric structure that arises through the transformation path along the <111>-*zb*-axis is the *rs*-phase. This allowed us to determine a spontaneous polarization value for the *zb*-crystals three times larger than that of the *wz*-phase. However, the lack of switching experiments in *zb*-structures (giant coercive fields) has limited the assessment of such polarization effects to interface charge measurements, from which, however, only the difference in formal polarization can be extracted. Moreover, giant interface charges can be mitigated by external species, incomplete surface coverage, or nonpolar surface reconstruction.[7] Thus, while the existence of giant polarization effects in such heterostructures cannot be ruled out, they might in practice not be easily accessible.

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LN-C-2 - Bonding of tetrahedral and hexagonal nitrides – ab initio picture

2. Physics and characterization

Stanislaw Krukowski[1]
Pawel Strak[1], Konrad Sakowski[1], Agata Kaminska[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142 Warsaw, Poland

Abstract text: Recent measurements of the properties the group III nitrides both AlN and GaN by soft x-ray emission spectroscopies revealed atypical feature of aluminum nitride (AlN) and gallium nitride (GaN). The valence band is composed of two separate subbands [1,2]. They are associated with different orbitals of metal and nitrogen atoms. For GaN the upper is composed of gallium hybridized and nitrogen orbitals, the lower of gallium *3d* and nitrogen *3s* orbitals. In case of AlN the lower is composed of nitrogen *2s* orbitals only. These data were confirmed by extensive *ab initio* simulations [1-3]. These results are not consistent with standard picture of tetrahedrally coordinated semiconductors in which bonding occurs between sp^3 hybridized orbitals of metal and nonmetal atoms. The application of new analysis techniques supported with ab initio simulation create a new picture of the bonding. Bonding occurs between resonant *p* states of nitrogen and sp^3 hybridized orbitals of metals that allows to preserve tetrahedral symmetry, in analogy to the bonding in benzene molecule [4]. Similar resonant bonding is observed in hexagonal BN where the p orbitals of nitrogen create three resonant states necessary for planar symmetry of the lattice. This is different from the bonding of graphene where carbon states are fully sp^2 hybridized.

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LN-C-3 - Experimental and DFT study of doped CrN thin films for thermoelectric applications

2. Physics and characterization

Niraj Kumar Singh[1]
Victor Hjort[2], Davide Gambino[2], Arnaud le Febvrier[1], Ganpati Ramanath[3], Björn Alling[2], Per Eklund[1]
[1] Department of Chemistry-Ångström Laboratory; Inorganic Chemistry, Uppsala University, Uppsala 75105, Sweden
[2] Department of Physics, Chemistry and Biology (IFM), Linköping University, SE-58183 Linköping, Sweden
[3] Rensselaer Polytechnic Institute, Department of Materials Science and Engineering, Troy, New York 12180, USA

Abstract text: Transition metal nitrides constitute an important class of functional materials which are mainly studied for their tribological applications but also possess promising thermoelectric properties.[1,2] Near room temperature, stoichiometric CrN shows high thermoelectric power factor (*PF*) of ~ 5 $\times 10^{-4}$ $Wm^{-1}K^{-2}$, however possess relatively higher thermal conductivity, $\kappa \sim 4$ $Wm^{-1}K^{-1}$.[3] Studying phase formation as a function of doping concentration supported by DFT calculations can provide crucial insights for the design of better thermoelectric materials for energy harvesting applications. We report on the phase formation of CrWxN thin films grown by reactive magnetron sputtering on c-plane sapphire substrate. W alloying led to a change of phase formation during film growth from CrN to metallic h-Cr_2N along with segregation of W. We observe a significant *PF* ~ 3.4 $\times 10^{-4}$ $Wm^{-1}K^{-2}$ in pristine CrN at room temperature.[4] Doping induced enhancement of σ is supported by density functional theory calculations which revealed shifting of Fermi level in the conduction band along with formation of acceptor states near the Fermi level. Increasing h-Cr_2N fractions in the $0.03 < x \leq 0.19$ range monotonically increases σ, but severely diminishes Seebeck coefficient leading to two orders of magnitude decrease in *PF*. This trend continues with $x > 0.19$ due to W precipitation. These findings indicate that dilute W additions below its solubility limit in CrN are important for realizing a high thermoelectric power factor in CrWxN films.

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LN-C-4 - Impact of Mg-threading screw dislocation complexes on electrical characteristics of GaN p–n junction diodes fabricated by thermal Mg diffusion

2. Physics and characterization

Takashi Murayama[1]
Yuta Itoh[1], Woong Kwon[1], Hirotaka Watanabe[2], Shugo Nitta[2], Atsushi Tanaka[2], Yosio Honda[2], Hiroshi Amano[2]
[1] Graduate School of Engineering, Nagoya University, Nagoya, Japan
[2] Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan

Abstract text: Localized p-type conductivity control in GaN is essential for the fabrication of vertical devices. Recently, Mg fast-diffusion has emerged as a simpler and potentially more scalable method for forming p-type GaN [1]. To assess the suitability of Mg-diffused structures for high-power devices, electrical characterization using p–n junction diodes (PNDs) is necessary. In typical MOVPE PNDs, complexes of Mg and threading screw dislocations (Mg-TSDs) can be critical leakage paths [2]. In this study, Mg-diffused PNDs were fabricated on GaN substrates with different threading dislocation densities (TDDs) to investigate the effect of TSDs on current leakage.

An n-type GaN layer ([Si] = 2.0×10^{16} cm^{-3}, 9 μm) was grown by MOVPE on GaN substrates with TDDs of 10^6 cm^{-2} (E6) and 10^4 cm^{-2} (E4). The Mg diffusion source was formed by shallow N and Mg implantation [3]. The dose and energy were 5.8×10^{13} cm^{-2} and 30 keV, respectively. AlN cap was deposited at 480°C, followed by annealing at 1300°C in N_2 for 5 min. Mg diffused approximately 1 μm from the surface, reaching a concentration of $0.4–1\times10^{18}$ cm^{-3}. Vertical deep-mesa PNDs were fabricated after AlN removal by TMAH [4]. Leakage sites were identified by *J–V* measurements and emission imaging, and threading dislocations were analyzed by cross-sectional TEM imaging.

Based on *J–V* measurements, most E6 devices exhibited significant leakage currents of $>10^{-5}$ A/cm² near –700 V, whereas the majority of E4 devices showed no leakage. Emission imaging of the leaking E4 and E6 samples confirmed that the leakage sites were located within the mesa areas. TEM of the leakage point identified a screw dislocation, indicating the presence of a Mg-TSD. In MOVPE-grown PNDs on E6 substrate, TSDs did not always act as critical leakage paths [4]. However, in Mg-diffused samples, nearly all TSDs served as leakage paths, which suggest that Mg fast diffusion promotes Mg-TSD-related leakage. Therefore, the use of low-dislocation-density substrates is particularly important when applying Mg diffusion to high-power devices.

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LN-C-5 - Operando Strain Microscopy in GaN/Si High Electron Mobility Transistors with Nanosecond Time Resolution

2. Physics and characterization

Cedric Corley-Wiciak[1]
Nicolas Til Sammler[2], Boris Butej[2], Agnieszka Anna Corley-Wiciak[1], Laura Neumann[3], Markus Sievers[2], Paul Antoine Douissard[1], Steven Leake[1], Carsten Detlefs[1], Michael Glavanovics[2], Michael Reisinger[2], Tobias Urs Schulli[1]
[1] ESRF - European Synchrotron Radiation Facility, 71 Avenue des Martyrs, 38000 Grenoble, France
[2] KAI - Kompetenzzentrum Automobil- und Industrieelektronik GmbH, A-9524, Villach, Austria
[3] Fraunhofer Institute for Ceramic Technologies and System (IKTS), Maria-Reiche-Straße 2, 01109 Dresden, Germany

Abstract text: High Electron Mobility Transistors (HEMTs) based on epitaxial (Al)GaN/Si heterostructures are emerging next-generation high-power and high-frequency electronic devices, due to their high breakdown voltage and fast switching speed. During high-voltage operation, particularly under hard switching conditions, the change of the electric field generates significant lattice strain at ns time scales, due to the piezoelectric nature of the Wurtzite crystal structure of (Al)GaN. This phenomenon provides a route for visualizing device operation, by monitoring the change of strain in nanoscale.

In this work, we present an *operando* strain microscopy study with ns time resolution of the thin $Al_{1-x}Ga_xN$ barrier and the GaN channel layer of an industrial fabricated p-GaN gate HEMT test structure, using Dark-Field X-ray Microscopy (DFXM) at the hard X-ray nanoprobe beamline ID01/ESRF. By a pump-probe approach leveraging the time structure of the synchrotron source and a dedicated sample setup for simultaneous recording of electrical and structural data, we obtain *operando* movies of the lattice strain in the HEMT during hard switching with down to 1 ns temporal and ~150 nm spatial resolution. We observe how the out-of-plane strain becomes more compressive in the regions covered by the gate electrodes and simultaneously more tensile around the drain during and after the hard turn-on. The magnitude of these strain fields is correlated in time with the electrical characteristics of the HEMT and reaches an amplitude of $\sim \pm 3*10^{-4}$ just before the turn-off.

Thus, we visualize the dynamic switching of a high-power device and provide valuable insight into the relation of electrical and mechanical strain in epitaxial (Al)GaN layers This experimental data may be used as a benchmark for Finite Element Method modeling for optimization of functional devices. Moreover, we showcase the new methodology of time-resolved strain microscopy with high-brightness synchrotron sources, allowing us to record dynamic movies of lattice strain rather than static images, which opens immense potential for a wide range of material systems within and beyond the III-V community.

LN-C-6 - Tuning Structure and Electronic Properties in Epitaxial $Sc_{1-x}W_xN_\gamma$ Thin Films on MgO(001): A Pathway to Engineered Nitride Materials

1. Growth

Susmita Chowdhury[1]
Hector Guerra Yanez[2], Sanath Kumar Honnali[1], Grzegorz Greczynski[2], Per O. Å. Persson[2], Arnaud le Febvrier[1], **Martin Magnuson**[2], Per Eklund[1]
[1] Inorganic Chemistry, Department of Chemistry - Ångström Laboratory, Uppsala University, Box 538, SE-751 21 Uppsala, Sweden
[2] Thin Film Physics Division, Department of Physics, Chemistry and Biology (IFM), Linkoping University, Linköping SE-581 83, Sweden

Abstract text: The effect of heavy atom incorporation, specifically tungsten (W), into scandium nitride (ScN) has been systematically investigated to understand its influence on the electronic structure and thermoelectric behavior of the resulting material. Due to the presence of 5d valence electrons, substitutional doping of W into the Sc sublattice is anticipated to shift the Fermi level into the conduction band. A continuous solid solution in the $Sc_{1-x}W_xN_\gamma$ system is theoretically plausible, given the relatively large lattice parameter of ScN among early 3d transition metal nitrides. However, phase separation is observed at W concentrations of $x \geq 0.10$, characterized by the formation of Sc-rich and W-rich domains via classical nucleation and growth mechanisms. At elevated temperatures (~800 °C), nitrogen substoichiometry emerges, driven by the generation of nitrogen vacancies and accompanied by the formation of secondary phases. Variations in the N/W ratio modulate the occupancy of nonbonding t_2g states within the valence band, contributing to electronic instability and phase segregation. Spectroscopic analyses reveal that the $Sc_{1-x}W_xN_\gamma$ system exhibits a reduced degree of covalency relative to pure ScN, indicative of increased ionic and metallic bonding character. Thermoelectric measurements show an unusual combination of a metal-like Seebeck coefficient with elevated electrical resistivity, distinguishing the $Sc_{1-x}W_xN_\gamma$ system from undoped ScN. This work provides a comprehensive assessment of the structural, microstructural, and electronic evolution of the $Sc_{1-x}W_xN_\gamma$ system and establishes its correlation with thermoelectric performance through an integrated experimental and theoretical framework.

Microscopy and dislocations

2025-07-11
08:30 - 10:00
Microscopy and dislocations

PC-Fri-1 - Fermi level pinning at nitride semiconductor surfaces and interfaces

2. Physics and characterization

Michael Schnedler[1]
Qianqian Lan[1], Lars Freter[1], Raphaël Butté[2], Nicolas Grandjean[2], Jean-François Carlin[2], Holger Eisele[3], Verena Portz[4], Qian Sun[5], Keyan Ji[1], Liverios Lymperakis[6], Philipp Ebert[1], Rafal E. Dunin-Borkowski[1]
[1] Forschungszentrum Jülich GmbH, Ernst Ruska-Centre (ER-C-1), 52428 Jülich, Germany
[2] Institute of Physics, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland
[3] Otto von Guericke Universität Magdeburg, Institut für Physik, 39106 Magdeburg, Germany
[4] Hamburger Fern-Hochschule, Department of Technology, 22081 Hamburg, Germany
[5] Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences (CAS), Suzhou 215123, China
[6] Department of Physics, University of Crete, Heraklion 70013, Greece

Abstract text: Fermi level pinning plays a crucial role in nitride semiconductor growth, contact formation, and the engineering of insulating layers. While pinning effects and carrier accumulation have been widely studied at nitride surfaces, their impact on interfaces remains equally significant. In this presentation, we explore Fermi level pinning at non-polar (10-10) surfaces and interfaces using scanning tunneling spectroscopy, off-axis electron holography (EH) in TEM, and complementary DFT calculations.

First we discuss the interplay of intrinsic surface states, defects, and air exposure on the Fermi level pinning at non-polar GaN, AlInN, AlGaN, and InN surfaces as well as the origin of electron accumulation. The empty group III-derived dangling bond is found to govern Fermi level pinning on most n-type group III nitrides, but not for InN, where defects dominate. Likewise for p-type doping defects govern the Fermi level pinning, too. Air exposure is found to shift pinning levels toward the band edges, attributed to water adsorption and dissociation, passivating intrinsic and extrinsic gap states. The results demonstrate that for all group III nitride semiconductors, including InN electron accumulation is not intrinsic, but rather extrinsically induced by adlayers.

Furthermore, we demonstrate the quantification of Fermi level pinning by EH in TEM using the example of focussed ion beam (FIB) implanted carbon. FIB preparation induces a Fermi level pinning about 0.7 eV above the valence band edge, attributed to C on N sites. Annealing experiments allow to probe the defect dynamics and barriers. Notably, it is demonstrated that carbon undergoes an atomic site-switching process, transitioning from a substitutional to an interstitial site where it becomes electrically inactive upon annealing. These findings provide a profound foundation for understanding the stability of insulating layers in ternary nitrides and offer critical insights for optimizing nitride-based electronic and insulating structures.

PC-Fri-2* - Nano-scale electron-beam-induced-current analysis of an electron-blocking layer and tunnel junction via scanning transmission electron microscopy

2. Physics and characterization

Konstantin Wein[1]
Holger Eisele[1], Gordon Schmidt[1], Frank Bertram[1], Peter Veit[1], Olga August[1], Christoph Berger[1], Armin Dadgar[1], André Strittmatter[1], Jürgen Christen[1]
[1] Institue of Physics, Otto-von-Guericke University Magdeburg, Magdeburg, Germany

Abstract text: In this work, we present an in-depth characterization of a triple-cascaded InGaN/GaN LED, each containing a pn-junction with multi quantum well (MQW) and an AlGaN electron-blocking layer (EBL), separated by a GaN:Ge/GaN:Mg tunnel junction (TJ). By correlating electron beam-induced current (EBIC) and cathodoluminescence (CL) measurements in a scanning transmission electron microscope (STEM), we analyze the impact of the internal electric fields on carrier transport, recombination, and injection dynamics at the nanoscale providing insight into carrier diffusion and drift in the vertical device.

Each LED consists of a Si-doped n-GaN layer (8×10^{18} cm^{-3}), an MQW of five $In_{0.11}Ga_{0.89}N$ QWs(2.5 nm thick) separated by undoped GaN barriers. A 17 nm Mg-doped $Al_{0.18}Ga_{0.82}N$ EBL is embedded between 23 nm and 210 nm thick Mg-doped p-GaN layers (2×10^{19} cm^{-3}). Together with the p-doped layer, a highly n-doped GaN:Ge layer (1×10^{20} cm^{-3}) forms the TJ, enabling efficient carrier injection into the next segment. Every LED is completed with an undoped AlGaN layer preventing Mg diffusion from underlying p-layers.

EBIC line scans along the growth direction reveal the highest current within the p-n junction of each segment. However, due to significant carrier recombination in the MQWs, the maximum EBIC signal shifts toward the EBL. This shift is attributed to (i) efficient carrier capture and recombination in the MQWs, depleting carriers before EBIC detection, (ii) band discontinuities at the AlGaN/GaN interface, impeding carrier transport in the space charge region, and (iii) polarization-induced charge separation at the AlGaN:Mg/GaN:Mg interface. These combined effects contribute to the observed EBIC maximum toward the AlGaN/GaN interface. These findings are supported by STEM-CL linescans at T = 17 K. We observe a maximum intensity of the spectrally integrated MQW emission at the 3rd QW and an abrupt MQW intensity drop at the EBL, indicating the underlying carrier separation and blocking.

In contrast, a weak EBIC response is detected at the TJ, despite its simulated electric field of ~4 MV/cm, far exceeding any other electric field amplitude in the structure. Drastically reduced CL intensity near the TJ interface suggests a locally low quantum efficiency due to efficient carrier separation. However, tunnel currents opposite in sign are assumed to reduce the overall EBIC signal.

PC-Fri-3* - Characterisation of porous gallium nitride via volumetric focussed ion beam scanning electron microscope tomography

2. Physics and characterization

Ben Thornley[1]
Maruf Sarkar[1], Jiawei Zhang[1], Thom R. Harris-Lee[1], Menno J. Kappers[1], Saptarsi Ghosh[2], Rachel A. Oliver[1]
[1] Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom
[2] Department of Electronic and Electrical Engineering, Swansea University, Swansea, United Kingdom

Abstract text: Porous gallium nitride (GaN), prepared by electrochemical etching (ECE), is a composite consisting of a GaN matrix and nanoscale pore networks. Porous GaN has increased the applications and versatility of GaN epitaxy in composites, optoelectronics and strain-relaxation engineering in heteroepitaxy.

Control of the porosity (%) and the scale/morphology of pore networks is possible through parameters such as ECE voltage, doping density, epistructure, electrolyte species/concentration and other variables. Processing/structure/property relationships for ECE of porous GaN are being extensively mapped out, with the aim that these variables can be dialled in to give a desired porosity, pore radius and branching rate. High resolution characterisation of the 3D structure of these pores is therefore essential.

We demonstrate that volumetric focussed ion beam scanning electron microscope (FIB-SEM) tomography is a powerful tool for pore characterisation, overcoming the limitations of alternative microscopy techniques. The basis is continuous milling and imaging; the ion beam is used to slice a fine layer of material away from a cross-sectional plane, and the electron beam is simultaneously used to image the cross-section of the porous sample. Through our optimisations to automation and 3D tracking, these SEM frames are compiled into a 3D reconstruction of the pores in the material. Our work will also discuss in detail the practicalities of capturing a tomograph, optimised for image stability and fine slicing width, and the extensive image processing performed for 3D reconstruction.

We demonstrate that tomography has permitted several discoveries about porous GaN in various etching and epilayer conditions. The structure of porous GaN epilayers etched in ultra-low concentrations of etchant was found by tomography to consist of many short pores that terminate at shallow depth, with a small number of pores extending down through the layer as unconventional, wide columnar structures. Tomographs of porous GaN DBRs etched at low voltage revealed a sharp drop-off in porosity in deeper porous layers, explaining their poor contribution to light reflectance. Finally, the etching of low-doped GaN was found to etch threading dislocations into nanopipes, forming ‘Christmas tree’ pores in ‘crown shy’ networks with porous ‘branches’ extending outwards on defined crystal planes.

PC-Fri-4* - Climb or Glide? — Revealing the Atomistic Dynamics of Threading Edge Dislocations in GaN

2. Physics and characterization

Han Yang[1]
Xuelin Yang[1], Guangxu Ju[1], Weikun Ge[1], Bing Huang[2], Bo Shen[1]
[1] School of Physics, Peking University, Beijing, China
[2] Beijing Computational Science Research Center, Beijing, China

Abstract text: Dislocation dynamics is the key to modulating dislocations in semiconductor materials. Understanding the motion of dislocations at the atomic scale may yield new phenomena not expected from conventional theory. A paradigmatic example arises in wurtzite III-nitride semiconductors. In GaN, the dominant threading dislocations (TDs) are threading edge dislocations (TEDs), possessing Burgers vectors b=1/3⟨11-20⟩ and {1-100} prismatic glide planes. During standard [0001]-oriented epitaxial growth, the prismatic TED glide planes minimize shear stresses on these defects. Consequently, the observed inclined TEDs have been attributed to dislocation climb. Such interpretations have driven theoretical models correlating stress evolution with dislocation climb. However, mounting experimental evidence contradicts this assumption: systematic TED inclination along ⟨11-20⟩ directions strongly suggest unconventional glide under epitaxial conditions. This empirical paradox exposes a critical knowledge gap in III-nitride defect physics—does TED inclination during crystal growth predominantly occur via climb or glide? Due to this controversy, atomic-resolution elucidation of TED migration pathways becomes imperative.

In this work, we propose and experimentally confirm a novel climbing mode of TEDs in GaN. This mode challenges emerging perspectives on long-range dislocation glide, yet differs from previous interpretations of dislocation climb. Based on the symmetric atomic structure of the dislocation core, TED undergoes pure climbing towards an orientation within the 60° range, in contrast to the single orientation of climbing proposed by conventional dislocation theory. Experimental statistics verify the new climbing mode and show that the dislocation climbing in the [-12-10] or [-2110] direction dominates in undoped GaN. Molecular dynamics (MD) calculations show that this type of climbing TED is energetically more favorable than the type predicted by the classical climb theory, confirming the experimental results. Both the experimental and theoretical results resolve the “climb-glide” controversy of TEDs in GaN during the epitaxial growth. It not only corrects the effect of dislocation climb on stress relaxation, but also deepens the understanding of the relationship between defect core structures and dynamic paths.

PC-Fri-5 - Impact of Dislocations on Leakage Currents of GaN-on-GaN pn-Diodes: A Statistical Approach Comparing X-Ray Topography with Electrical Characteristics

2. Physics and characterization

Roland Weingärtner[1]
Leon Schiller[1], Alexander Kinstler[2], Richard Neumann[2], Frank Brunner[3], Eldad Bahat Treidel[3], Enrico Brusaterra[3], Matthias Marx[4], Sven Besendörfer[1]
[1] Fraunhofer Institute for Integrated Systems and Device Technology IISB, Schottkystr. 10, Erlangen, Germany
[2] Infineon Technologies AG, Am Campeon 1-15, 85579 Neubiberg, Germany
[3] Ferdinand-Braun-Institut gGmbH (FBH), Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany
[4] AIXTRON SE, Dornkaulstraße 2, 52134 Herzogenrath, Germany

Abstract text: The wide-bandgap semiconductor gallium nitride (GaN) draws increasingly industrial attention for power electronic applications. However, performance of devices based on heteroepitaxy suffers from the high defect densities of the epilayer. In addition, thick layers for vertical device structures which support high voltage are difficult to obtain with low bow. Therefore, GaN-on-GaN based device technology is a desired approach.

Typically, the relation between material defects such as dislocations and device performance are investigated on a small, microscopic scale or on heteroepitaxial based devices [1, 2]. In this framework we investigate the impact of dislocations in the GaN substrate and consequently the epilayer on diode performance on full wafer scale. On five HVPE-grown 2”-GaN substrates we fabricated 552 vertical pn-diodes each with effective areas of 3.0, 6.0 and 12.0 × 10^{-4} cm^{-2} in checkerboard pattern throughout the wafer. The leakage current of the pn-diodes is highly sensitive to either point defects or dislocation content while fluctuations in technological process steps have little influence. It is the aim of this work to differentiate between these effects by a large statistical approach. X-ray topography is used to characterize the substrate with epilayer and the wafer with devices on top using Cu:0004 reflection. Macro-defects like wafer preparation damages and V-pits can be identified under the diodes’ active areas in the topographs and directly correlated to their IV-characteristics. We show that X-ray topography not only reveals dislocation networks in the epilayer, but also that diffraction intensity is correlated to the dislocation density and thus influences the leakage current of the diode. The latter effect is investigated at high blocking voltages at -700V where still most diodes don´t show electrical breakdown.

Conclusively, we show that besides of technological processing impact on the leakage current, also the dislocation network of the epilayer must be considered to understand the reverse bias characteristics and should be considered in device processing.

[1] Besendörfer, et. al. (2020), Sci. Reports 10 17252.

[2] Brunner, et al., physica status solidi (RRL) – Rapid Research Letters, vol. 18, no. 11, Nov. 2024, doi: 10.1002/pssr.202400013.

Visible LEDs: defects and tunnel junctions

2025-07-11
08:30 - 10:00
Visible LEDs: defects and tunnel junctions

OD-Fri-1 - Origin of non-radiative point defects in InGaN/GaN quantum wells

3. Optical devices

Nicolas Grandjean[1]
[1] Institute of Physics, Ecole polytechnique fédérale de Lausanne (EPFL), Switzerland

Abstract text: For decades, dislocations have been considered the main factor limiting the internal quantum efficiency (IQE) of InGaN/GaN quantum wells (QWs) in blue light-emitting diodes. Recently, it has become clear that point defects (PDs) are just as important. The presence of these point defects in QWs has been shown to be related to the growth temperature of the GaN buffer layer, but their origin and nature are still unknown.
In this presentation, we will report on recent experiments that highlight the critical role of the stability of the c-plane GaN surface with respect to temperature and ammonia overpressure on the IQE of InGaN/GaN QWs. This leads us to propose a mechanism for the formation of PDs in QWs that create efficient non-radiative centers. Finally, we will discuss the relative weight of PDs and dislocations on the efficiency of QWs.

OD-Fri-2* - Influence of Tail States distribution on Carrier Injection in RGB InGaN MQW LEDs including V-defects and Random Alloy fluctuations

3. Optical devices

Huai-Chin Huang[1]
Claude Weisbuch[2], James S. Speck[2], Yuh-Renn Wu[1]
[1] Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taiwan
[2] Material Departments, University of California, Santa Barbara, USA

Abstract text: Red InGaN-based LEDs are challenged by high lattice mismatch and strong piezoelectric polarization fields. These fields lead to a strong QCSE and create polarization-induced barriers, making carrier injection difficult. Hence, random alloy fluctuations and V-defects play vital roles in red LEDs in reducing the forward voltage [1]. However, experimental observations reveal the leakage currents at low biases [2]. Dislocation lines (TDs) may trap carriers, causing nonradiative recombination. To resolve this discrepancy, we incorporate an additional leakage mechanism into our analysis by introducing tail states that may originate from crystal imperfections, strain-induced bandgap variations, random doping effecting, or impurities. In our study, tail states are modeled using a Gaussian distribution density of states (N_{tail}) with energy distribution width (σ). The simulation method used the 2D-DDCC program in red InGaN MQW LEDs by including the effects of random alloy fluctuations and V-defects. We vary the tail state parameters to examine their impact at threading dislocation centers and V-defect sidewalls.

The electron and hole distributions show that the incorporation of tail states increases leakage currents and nonradiative recombination. This additional leakage pathway leads to a better match with the experimentally observed current-voltage characteristics at low biases ($V<V_{turn-on}$). Tail states in TDs result in strong leakage and enhanced nonradiative recombination. In contrast, those at the V-defect sidewalls reduce the barrier for carrier injection, thereby enhancing current injection efficiency. At lower voltages, tail states alter current behavior by enhancing injection while also increasing leakage and nonradiative losses if they flow to the TD centers. The different densities of N_{tail} and present a different degree of leakage current below the turn-on voltage. On the other hand, the tail state also significantly reduced the forward voltage. Hence, the optimized condition between IQE and WPE must be found. For optimizing carrier injection with V-defect while mitigating leakage and nonradiative losses, controlling the N_{tail} during growth is essential. This new loss mechanism needs to be considered for device design and optimization.

[1] C.-H Ho, et al., Physical Review Applied 17, 014033, (2022)

[2] J. Park, et al., Optics Express 32, 24242 (2024)

OD-Fri-3* - V-pits and trench defects in GaN-based optoelectronic devices: Extensive characterization and modeling

3. Optical devices

Carlo De Santi[1]
Marco Nicoletto[1], Alessandro Caria[1], Nicola Roccato[1], Matteo Buffolo[2], Fabiana Rampazzo[1], Giovanna Mura[3], Francesca Rossi[4], Xuanqui Huang[5], Houqiang Fu[5], Hong Chen[5], Yuji Zhao[6], Andrea Gasparotto[7], Conny Becht[8], Gunnar Kusch[9], Yihong Ji[9], Rachel Oliver[9], Ulrich T. Schwarz[8], Gaudenzio Meneghesso[1], Enrico Zanoni[1], Matteo Meneghini[2]
[1] Department of Information Engineering, University of Padova, Padova, 35131, Italy
[2] Department of Information Engineering and department of Physics and Astronomy, University of Padova, Padova, 35131, Italy
[3] University of Cagliari, Cagliari, 09124, Italy
[4] CNR IMEM, Parma, 43124, Italy
[5] Arizona State University, Tempe, AZ 85287, USA
[6] Department of Electrical and Computer Engineering, Rice University, Houston, 77005, USA
[7] Department of Physics and Astronomy, University of Padova, Padova, 35131, Italy
[8] Institute of Physics, Chemnitz University of Technology, Chemnitz, 09126, Germany
[9] Cambridge University, Cambridge, CB3 0FS, United Kingdom

Abstract text: This work presents an in-depth analysis on the electrical and optical properties of V-pits and trench defects in multiple quantum well-based gallium nitride optoelectronic devices.

The presence of V-pits was included in numerical simulations in TCAD Sentaurus. A strong improvement in carrier injection efficiency and current level below the turn-on of the diode is detected when the V-pits reach the quantum wells. The effect depends on the number of affected quantum wells, and optimized simulations can accurately reproduce the experimental characteristics. [1]

High-resolution light beam induced current (LBIC) measurements carried out in low forward bias (below the turn-on voltage of the diode) confirm the injection efficiency improvement in the location where V-pits are present and in correspondence of V-pit clusters forming trench defects. [2] In these positions μ-EL spectra show the presence of a second EL peak, significantly redshifted in the trench defects compared to the emission from the rest of the sample. [3]

The origin of the redshift can be understood by microscopic analysis of the cross-section of the trench defect. An increase in indium incorporation inside the trench defect is clearly visible in spatially-resolved energy-dispersive X-ray spectroscopy (EDX) measurements, leading to the redshift in the emission detectable by the cathodoluminescence (CL) wavelength map. [4]

The experimental findings were confirmed testing devices with thicker p-GaN, leading to better V-pit filling and lower effect on the electrical and optical characteristics.

[1] 10.1109/JPHOTOV.2023.3311891 [2] 10.1063/1.4768291 [3] 10.1109/TED.2024.3353711 [4] M. Nicoletto *et al.*, manuscript under preparation

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“Network 4 Energy Sustainable Transition—NEST”, Spoke 1., Project code PE0000021, funded under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.3— Call for tender No. 1561 of 11.10.2022 of Ministero dell’Universita` e della Ricerca (MUR); funded by the European Union—NextGenerationEU. The CL facility was funded by EPSRC under EP/R025193/1.

OD-Fri-4 - Bicolor cascaded GaN-based LEDs with GaN:Mg/GaN:Ge tunnel junctions

3. Optical devices

Christoph Berger[1]
Armin Dadgar[1], André Strittmatter[1]
[1] Otto-von-Guericke-University Magdeburg, Germany

Abstract text: Cascaded light-emitting diodes (LEDs) with separate InGaN/GaN-MQW active regions interconnected by tunnel junctions (TJs) offer higher efficiency as well as individual on-device color mixing. In this work, we demonstrate first experiments on MOVPE-grown two-color cascaded LEDs featuring green-emission color from the top LED and blue-emission from the bottom LED which are connected in series by a GaN:Ge/GaN:Mg tunnel junction. Performing no post-growth annealing step for p-GaN activation, electroluminescence intensity of the green LED section is already comparable to previously reported blue LEDs with TJs, while the current-voltage characteristic exhibits a voltage penalty of around 1 V due to a non-optimized doping profile of the TJ in this LED section. However, the buried blue LED section suffers from strongly increased operation voltage and non-homogeneous, punctual luminescence. From X-ray diffraction and luminescence spectroscopy as well as annealing experiments, changes of the InGaN/GaN multi-quantum well section during overgrowth can be excluded to large extent. Secondary ion mass spectroscopy shows that Mg atoms from the p-GaN region diffuse into the bottom MQW section. Post-growth annealing at 750°C in nitrogen for 1 hour after mesa formation helps to improve electrical and optical characteristics of the buried blue LED section, which is a fingerprint of insufficient Mg activation during growth. Thereby, homogeneous luminescence of the blue LED section was achieved for 300x300 μm^2 large LEDs. However, the post-growth annealing caused an increase of the forward voltage of the green LED section due to Mg and Ge diffusion at the TJ-interface. A study on growth process parameters was conducted aiming at reduced Mg diffusion and improved light output of the cascaded LED. Lower growth temperature and shorter duration of growth process steps following the bottom blue LED section significantly increased its optical emission intensity. Also the growth temperature of the Si-doped GaN layer as part of the pn-junction of the top green LED section takes impact on luminescence intensity, which may be associated with recent discussions on non-radiative point defects in the low-temperature GaN underlayer.

OD-Fri-5 - Understanding the inner state of InGaN-based micro-LEDs

3. Optical devices
Jeong-Hwan Park[1]
Markus Pristovsek[2], Hiroshi Amano[2]
[1] Nagoya University, current address: Samsung Electronics
[2] Nagoya University

Abstract text: To realize the full color without indirect methods (e.g., quantum dot, color filter) for augmented reality (AR), III-V based micro-LEDs (μLEDs) are attractive. As for blue and green light sources, InGaN-based μLEDs are mature, the most efficient and reliable material compared to other light sources. As for the red-light source, however, both AlGaInP and InGaN-based red μLEDs are being competitively developed due to their different characteristics. For example, Lumileds directly compared external quantum efficiency (EQE) of a few microns sized red μLEDs either AlGaInP and InGaN-based and demonstrated that the EQE of InGaN red μLEDs is independent of the size and becomes even more efficient at lower current density [1]. This size-independent behavior is important regarding ultra-small sized μLEDs for AR displays since the high pixel density requires maximum efficiency. Thus, a fundamental understanding of the performance of InGaN-based red μLEDs is a key factor in realizing highly efficient AR displays.

We experimentally found that non-radiativethe sidewall-surface recombination is determined by the inner state of InGaN μLEDs. First, through the comparison of devices that have ~1.5×10^8 cm^{-2} and > 10^9 cm^{-2} defect density, a device with high defect density suffers less from the sidewall-surface recombination, resulting in no significant size-dependent degradation [2]. Second, the observation of indium fluctuation for different indium content (e.g., 30, 15, and 7.5%) InGaN layer through atom probe tomography (APT) finds the relationship between indium fluctuation and diffusion length of carrier [3]. For example, EQE of InGaN blue μLEDs remarkably decreases with shrinking size in which behavior is more serious without TMAH chemical treatment, contributed by the long diffusion length of the carriers. Meanwhile, the EQE of InGaN red μLEDs does not rely on the size as well as sidewall condition.

To conclude, a better physical understanding of how the inner state of μLEDs affects the carrier movement gives guidance to realize ultra-small and high-efficiency μLEDs.

[1] Moran *et al*., *SID symposium Digest of Technical Papers*, **54**, 414 (2023).

[2] Park *et al*., *Laser Photonics Rev.*, **17**, 2300199 (2023).

[3] Park *et al*., *Appl. Phys. Rev.*, **11**, 041427 (2024).

Novel Electronic Devices 5 (Devices)

2025-07-11
08:30 - 10:00
Novel Electronic Devices 5 (Devices)

ED-Fri-A1* - Enhanced Spreading of Photon-Generated Holes by Double-Channel Structre in p-GaN Gate Double-Channel HEMT to Suppress Back-Gating Effect

4. Electronic devices

Zheng Wu[1]
Tao Chen[1], Yat Hon Ng[1], Haochen Zhang[1], Zongjie Zhou[1], Yan Cheng[1], Hang Liao[1], Yutao Geng[1], Kevin Jing Chen[1]
[1] The Hong Kong University of Science and Technology, HKUST, Hong Kong, China

Abstract text: The monolithic integration of GaN high-electron-mobility transistors (HEMTs) and peripheral circuits provides a solution to unlock the full potential of GaN-on-Si technology for high-frequency applications [1]. However, the half-bridge topology, which consists of a high-side (HS) switch and a low-side (LS) switch, presents challenges for monolithic integration on the conventional platform. The use of a common Si substrate makes it impractical to implement the substrate-to-source (STS) termination for each transistor. Consequently, the HEMT that lacks the STS termination suffers severe degradation in static or dynamic on-resistance (R_{ON}) due to the back-gating effects [2]. Prior arts, including the employment of engineered substrates and implementation of a virtual body have demonstrated the suppression of the back-gating effects [3-5] with more costly substrate engineering, new buffer design and all request trenches for isolation.
In this work, we investigate the back-gating effects in a *p*-GaN gate *double-channel* HEMT (DC-HEMT) under *UV illumination.* Our findings indicate that the upper channel plays a crucial role in hole spreading, which facilitates efficient spreading of photon-generated holes to the gated region. When a *p*-GaN Schottky-type gate DC-HEMT is subjected to UV illumination, electron-hole pairs are excited in the access regions by incident photon from an external 340-nm UV light-emitting diode (LED) and subsequently separated by the electric field originating from the Si substrate bias (V_{SUB}). Regarding the photon-generated holes, those generated in the upper channel are partially blocked by the thin AlN barrier layer between the two channels. Moreover, the vertical electric field from V_{SUB} enhances the carrier confinement at the hetero-interface, allowing holes to spread along the lower portion of the upper channel and provide effective shield and compensation to the upper and lower channel, respectively. Consequently, the device characteristics of the DC-HEMT under UV illumination are well protected and free from any adverse effects from negatively biased Si substrate, which highlights the potential of the *p*-GaN gate double-channel platform for power integration in a synchronous gate/LED driving mode.
Acknowledgement: This work is supported by Hong Kong RGC Strategic Topics Grant (STG) under STG3/E-602/23N and RGC GRF under project 16209423.

ED-Fri-A2* - Nanosheet Double-gate AlGaN/GaN Transistors Design and Fabrication

4. Electronic devices

Gillian Micale[1]
John Niroula[1], Jung-Han Hsia[1], Pradyot Yadav[1], Hridibrata Pal[1], Tomás Palacios[1]
[1] Microsystems Technology Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Abstract text: The high breakdown voltage and high electron saturation velocity of GaN have made this material platform a leading choice for high-power and high-frequency applications. Scaling has allowed GaN high electron mobility transistors (HEMTs) to reach impressive operation frequencies, however decreasing device dimensions has given rise to troubling short channel effects (SCEs) and low power density. A double-gate (DG) architecture has gained interest as a new paradigm for managing SCEs in III-V devices with experimental demonstrations for GaAs HEMTs showing high transconductance and frequency performance as well as improved functionality based on the back gate bias condition [1]. For GaN HEMTs, the DG design should facilitate a tunable threshold voltage and improved current density, transconductance, and oscillation frequency while suppressing SCEs. [2]

We explore a novel AlGaN/GaN DG-HEMT architecture, describing device operation with TCAD simulations and experimental results while highlighting key processing steps. The device fabrication utilizes thermal compression wafer bonding with a hydrogen silsesquioxane (HSQ) interlayer and flip-processing followed by removal of the original substrate to create the stacked gate-channel-gate structure. The proposed HSQ bonding method is CMOS compatible with a high thermal budget and good heat dissipation [3], and the processing temperature of 400°C makes this method transferable to InAlN barrier devices and other technologies like back-end heterogeneous integration. Compared to single-gated HEMTs, the double-gate structure offers greater resilience to drain-induced barrier lowering enabling greater access to high voltage operation for short channel devices, and the increased current density and tunable threshold voltage will lower overall power consumption.

Acknowledgements
We thank SOITEC for their support and advisement. This work was supported in part by Center 7 SUPREME: SUPeRior Energy-efficient Materials and dEvices, one of the seven centers in JUMP 2.0, a Semiconductor Research Corporation (SRC) program sponsored by Defense Advanced Research Projects Agency (DARPA) under the award no. 145105-21913.

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ED-Fri-A3* - Al-rich AlGaN multi-channel nanowire transistors with d-AlGaN regrown contacts prepared via pulsed sputtering

4. Electronic devices

Takao Kozaka[1]
Kohei Ueno[1], Hiroshi Fujioka[1]
[1] Institute of Industrial Science, The University of Tokyo, Tokyo, Japan

Abstract text: In this study, we demonstrate Al-rich AlGaN multi-channel nanowire transistors with regrown contact of n^{++} Al-rich degenerate AlGaN (d-AlGaN) prepared via pulsed sputtering, achieving precise sidewall gate control, low on-resistance ($R_{ON, SP}$) of 2.5 mΩcm^2 and breakdown voltage (BV) as high as 2.7 kV.

Although AlGaN based HEMTs are quite attractive for high-power applications, the devices reported so far generally exhibit high device resistance in the on-state due to low channel conductance and high contact resistance with the metal electrode. To improve the channel conductance practically, the use of AlN/AlGaN multichannel structures that generate multiple 2DEG layers within a high breakdown voltage matrix is expected. By stacking the 2DEG channels, we can boost the net sheet electron density while maintaining electron mobility, effectively mitigating the conventional trade-off between BV versus $R_{ON, SP}$. To reduce the contact resistance between channels and electrodes, regrowth of n^{++} Al-rich degenerate AlGaN is expected to be promising.

Here, we report that three-dimensional architectures composed of AlN/Al-rich AlGaN multi-channel structures and n^{++} Al-rich AlGaN regrown ohmic contacts via pulsed sputtering deposition (PSD). Pulsed delivery of high-energy precursors promotes surface migration of atoms even at low temperatures, thus suppressing the formation of misfit dislocations and enabling coherent growth of high-quality multichannel AlN/AlGaN structures. For example, Reciprocal Space Mapping (RSM) confirms coherent growth of AlN/$Al_{0.6}Ga_{0.4}N$ 8-channel structures without lattice relaxation, yielding a low sheet resistance of 949 Ω/s. Furthermore, employing the sputter regrown ohmic contacts of n^{++} Al-rich AlGaN with an electron concentration exceeding 1×10^{20} cm^{-3} resulted in a contact resistance below 1 Ωmm for single-channel of Al compositions ranging from 50% to 71%. The AlN/AlGaN multi-channel transistors with slanted tri-gates and the regrown contact demonstrated a successful gate modulation with a single-peaked transconductance, low Ron,sp = 2.5 mΩcm^2, and BV = 2.7 kV. This is the lowest Ron,sp among UWBG transistors with BV > 1 kV to date. These results indicate that the PSD AlN/AlGaN multichannel architecture with d-AlGaN contacts has great potential for high-voltage and high-power device applications.

ED-Fri-A4 - UWBG Ferroelectric ScAlN/AlGaN High-Electron Mobility Transistor

4. Electronic devices

Md Tanvir Hasan[1]
Jiangnan Liu[1], Andrew Armstrong[2], Brianna Klein[2], Andrew Allerman[2], **Zetian Mi**[1]
[1] University of Michigan, Ann Arbor
[2] Sandia National Laboratories

Abstract text: UWBG AlGaN-channel HEMTs exhibit excellent electron transport, with ~50% Al achieving a breakdown field of >10 MV/cm and a saturation velocity >1.5×10^7 cm/s. However, challenges such as poor ohmic contacts and current collapse persist. Advances include a high drain current (~1.3 A/mm), record-low contact resistance (0.25 Ω·mm), and stable operation at 600°C, making them suitable for RF, high-power, and high-temperature applications. Recently, the introduction of ScAlN barriers has enhanced polarization engineering, improving device performance. Key results for ScAlN/GaN HEMTs include a high 2DEG density (~6×10^{13} cm^{-2}) with 710 $cm^2/V\cdot s$ mobility, I_D > 4 A/mm with f_{max} >130 GHz, and stable operation at 423°C. Its ferroelectric nature enables nonvolatile memory, achieving a 3.8 V V_{th} tuning range and an I_{ON}/I_{OFF} of 3×10^7. While integrating ferroelectric ScAlN with AlGaN holds promise for multifunctional devices, it has not been demonstrated yet. This study presents the first experimental realization of a ferroelectric HEMT with an MBE-grown $Sc_{0.15}Al_{0.85}N$ barrier and MOCVD-grown $Al_{0.50}Ga_{0.50}N$ channel, enhancing 2DEG density through strong polarization and large conduction band discontinuity.

Fig. 1 shows the device schematic (a), top-view of SEM image (b), energy band diagram (c), and fabrication process (d). Fig. 2 presents output (a) and transfer (b) curves, showing a maximum I_D of ~16.3 mA/mm at V_{GS} = 1 V with a R_{on} ~340 Ω·mm, and I_{ON}/I_{OFF} of 2.3×10^6 at V_{DS} = 5 V. The gate leakage (5.53×10^{-6} mA/mm), same as the off-current, indicates high epitaxial quality. A V_{th} shift (Fig. 3(a)) in the backward sweep suggests electron trapping, with counterclockwise hysteresis indicating ferroelectric charge coupling. The ΔV reaches 6.4 V at V_{DS} = 1 V, which is ~4× than reported ScAlN/GaN HEMTs. The lowest SS (~65 mV/dec) (Fig. 3(b)) approaches the Boltzmann limit, confirming potential for memory applications. Figs. 4(a) and (b) shows I_D increasing with temperature, reaching 3.75× and 2.47× its RT values at 400°C for V_{DS} = 1 and 5 V, respectively, probably due to thermionic emission. The leakage current (Fig. 4(c)) increased to ~10^{-5} mA/mm at 400°C, an order higher than RT.

These results establish ferroelectric ScAlN/AlGaN HEMTs as promising platform for nonvolatile, reconfigurable power, and high-temperature memory applications.

ED-Fri-A5 - Acoustically Actuated Scalable Wide Bandgap III-Nitride Switch

4. Electronic devices

Hang Cui[1]
William Schaffer[1], Daqi Han[1], Xiang Miao[1], Emily Marshall[1], Paul Stephen[1], Lukas Graber[1], **Douglas Yoder**[1], Alan Doolittle[1]
[1] Georgia Institute of Technology, Atlanta, GA, USA

Abstract text: We present an original approach to power switching technology featuring scalability up to power grid levels. Unlike all other power transistor technologies, the Piezo-Acoustic Transistor (PAT) lacks an electrically driven gate electrode, rendering it highly resistant to noise, and greatly reducing the complexity required for switching circuitry. Electrical current through the PAT is modulated instead by a piezoelectric transducer. When triggered, the transducer applies uniaxial compressive stress along the c-axis to a wurtzite III-Nitride epitaxial layer structure, altering the net polarization charge at each interface by virtue of piezoelectric contrast. Modulation of interfacial polarization charge forms and extinguishes conducting channels between remote lateral electrodes. As a consequence of the PAT's structural symmetry, current flow within the PAT is bi-directional, reducing the device count required for many power conversion applications.

PAT performance is limited primarily by device geometry rather than fundamental physics. The distance between lateral electrodes controls blocking voltage, and device width and/or thickness determine on resistance. Moreover, applied pressure is distributed evenly within the active region after a brief acoustic switching transient, guaranteeing uniform channel conductivity. Unlike conventional semiconductor power switches, a PAT device accommodates top- and bottom-side heat sinks, making heat extraction more than twice as efficient.

Structural, elastic and piezoelectric properties of non-conventional wurtzite III-N materials are calculated by DFT, and are used to elucidate the piezo-conductive effect for various heterointerfaces. Solutions of electrostatically self-consistent charge transport equations enable the determination of channel mobility and ultimately on and off resistances as a function of device length and width, and the number of channels grown. A process flow is demonstrated to realize tapered rather than vertical sidewalls, facilitating electrical access to multiple channels. FE simulations of uniaxial compressive stress reveal distribution of force throughout the PAT, and suggest design modifications to minimize plastic deformation. Together, these features predict 10s-100's kV operation at currents limited only by total device thickness and associated heat dissipation limits.

Pilot lines and critical processes

2025-07-11
08:30 - 10:00
Pilot lines and critical processes

ED-Fri-B1 - Wide Band Gap Pilot Line: challenges and opportunities for the next generation of semiconductor technologies

4. Electronic devices

Fabrizio Roccaforte[1]

[1] Consiglio Nazionale delle Ricerche – Istituto per la Microelettronica e Microsistemi (CNR-IMM) Strada VIII, n. 5 – Zona Industriale, 95121 Catania – Italy

Abstract text: Nowadays, the increasing need for electric energy is driving the development of new semiconductors technologies, with better efficiency and lower power consumption with respect to silicon (Si). Owing to their outstanding properties, wide band gap (WBG) semiconductors, like silicon carbide (SiC) and gallium nitride (GaN), can guarantee better performances than Si and have progressively entered the high-power and high-frequency devices markets, in several strategic fields (e.g. automotive, consumer electronics, telecommunications, transportation, datacenters, aerospace, industry, etc.). These materials have gained traction in the semiconductor industry, although their technological platforms are not yet as mature as Si. Hence, WBG devices manufacturing processes and architecture must be further explored to open novel applications and improve energy efficiency. Moreover, materials costs must become more affordable to avoid limitations on the market's adoption. Besides SiC and GaN, Ultra-WBG (UWBG) semiconductors, e.g. gallium oxide (Ga_2O_3), aluminum nitride (AlN) and diamond, are currently explored for future ultra-high-power applications and quantum technologies. However, their wafer size and crystal quality are still insufficient for processing in the industrial environment.

In general, for devices manufacturers, the intermediate stages of products development are characterized by high costs and significant risks, which can become major bottlenecks when moving from R&D to mass production. Hence, the creation of *pilot lines* can bridge the gap between R&D demonstration in the lab and large-scale industrialization, ensuring a smoother transition to production and reducing the overall risks.

The *WBG Pilot Line* aims at creating an integrated infrastructure focused on the development of WBG semiconductors technologies for power- and high-frequency electronics. The project, funded by Chips JU and National Authorities, will be implemented by a Consortium distributed in seven EU countries (Italy, Poland, Sweden, France, Austria, Germany and Finland), involving Universities and Public Research Centres with a recognized experience in the field of advanced semiconductors technologies. The WBG Pilot Line will address all the *critical processing issues* related to materials growth and devices fabrication based on both WBG and UWBG semiconductors, refining the roadmap of such technologies. The project outcomes and the “know-how” developed within this initiative will be a boost for innovation and competitiveness in Europe, by creating new carrier opportunities for young researchers, and a fertile environment for large device manufacturers and small companies to test and validate new technologies and to explore new market segments.

ED-Fri-B2 - Initial Pilot Line of 300mm GaN on Silicon HEMT Devices by Infineon

4. Electronic devices

Claudio Canizares[1]
Lidia Lupina[2], Andreas Jamnig[2], Hao Zhou[1], Milan Forcan[1], Thomas Wuebben[2]
[1] Power and Sensor Systems, Infineon Technologies Austria AG, Villach, Austria
[2] Frontend Technology, Infineon Technologies Austria AG, Villach, Austria

Abstract text: We present an update on Infineon's process of creating GaN HEMT devices on 300mm diameter Si substrates. Not only does the use of 300mm Si allow for 2.3 times more chips per wafer, but it also permits for the use of more advanced semiconductor production equipment, opening up the path for greater advances in future chip and technology design. Infineon is also in the unique position to incorporate GaN transistor production along with an existing high level Si manufacturing line, therefore reducing the overall capital requirement. This will help GaN HEMTs achieve cost parity with Si devices over time.

We present the results from the conversion of a 200mm production line to a 300mm fabrication facility. The epitaxial material is made in-house and important figures of merit are compared to our production process in 200mm, such as wafer bow and crystal quality. We show excellent within-wafer and wafer-to-wafer uniformity, and the ability to tune the device layers to get 2DEG properties matching our current production. We also describe a contamination mitigation concept to prevent cross-contamination in our 300mm high volume Si production line.

Finally, we present electrical results comparing devices made from our standard 200mm process and our developing 300mm fabrication process, including matching forward threshold voltage and vertical breakdown. This shows that Infineon is on the path to developing a high volume manufacturing line for 300mm GaN in its existing Si power fab.

ED-Fri-B3 - Formation of deep and gradual GaN p-n junctions for edge termination using channeled Mg/N-ions implantation and ultrahigh pressure annealing

4. Electronic devices

Tetsuo Narita[1]
[1] Toyota Central R&D Labs., Inc.

Abstract text: An electric field crowding is one of the limitation factors for a performance of a vertical GaN power device. A deep and gradual junction formed by channeled ion implantation can relax the electric field at a junction and allows robust design of junction termination extensions [1]. This study compared junction properties formed by channeled Mg/N ions implantation with those by random ion implantation.

Lightly n-type GaN layers were formed on homoepitaxial n^+-type GaN layers using metalorganic vapor phase epitaxy (MOVPE). Mg and N ions were implanted with multiple energies into the n-type layers to obtain the 3×10^{17} cm^{-3} box-shape profile. Then, conditions of random and channeled implantations were applied. Post-implantation annealing was carried out at 1300 ºC under 500 MPa of nitrogen gas ambient for 30 or 60 min. After that, p^+-type GaN contact layers were grown by MOVPE, followed by dehydrogenation annealing. Through sloped mesa isolation and electrode formation, p-n diodes were formed.

Secondary ion mass spectrometry (SIMS) analyses revealed minimal diffusion of Mg atoms by controlling the sequential N-ion profiles [2] even after UHPA for 60 min, indicating robustness of the process. Both implantation conditions produced forward bias properties with ideality factors of 2, indicating recombination current in good p-n junctions. The p-n diodes formed by channeled implantation exhibited less reverse leakage due to the deep and gradual doping profiles. The acceptor concentration N_a was examined as a function of depth using capacitance–voltage (C–V) curves. For the random implantation, N_a was below 10% of dopants after 30 min-UHPA, resulting in full depletion of the p-type layer, while was improved to 25 % after 60 min-UHPA. In contrast, the higher N_a values (~60%) were obtained even after 30 min-UHPA for the channeled implantation, which was also confirmed by scanning nonlinear dielectric microscopy (SNDM). Furthermore, hysteresis in C–V curves due to residual point defects was reduced for channeled implantation. Rapid recover of implantation damage and a deep gradual junction are advantages of channeling process for termination of vertical GaN devices.

This work was supported by the MEXT program (Grant no. JPJ009777).

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ED-Fri-B4* - High Field Performance of Si-doped n-AlN Layers grown using Pulsed MOCVD

4. Electronic devices

Tariq Jamil[1]
Abdullah Al Mamun Mazumder[1], Mafruda Rahman[1], Muhammad Ali[1], Grigory Simin[1], Asif Khan[1]
[1] Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208, USA

Abstract text: Recently we have reported on a new pulsed metalorganic chemical vapor deposition (PMOCVD) process for n-type Si-doping of AlN homoepitaxial layers. It was shown to yield a higher doping efficiency than conventional MOCVD. Here we report a study of the high-field performance of the PMOCVD Si-doped homoepitaxial *n*-AlN layers by incorporating them as the drift layer in a quasi-vertical conduction Schottky barrier.

The epilayer structure of our study comprises of 250 nm thick undoped AlN/300 nm undoped i-$Al_{0.8}Ga_{0.2}N$ buffer layers followed by a 1 µm thick silicon doped *n*-contact formation n^{++}-$Al_{0.7}Ga_{0.3}N$ layer. Then a 100 nm thick undoped graded composition $Al_xGa_{1-x}N$ layer (x from 0.7 to 1.0) is added to compensate the band offset at the n^{++}-AlGaN/*n*-AlN drift layer interface. Using mercury probe CV measurements, we determined its carrier concentration to be around 3.5×10^{17} cm^{-3}. Finally, a 0.4 µm thick Si-doped *n*-AlN drift layer which is deposited using the PMOCVD procedure as described in our recent publication. All the layers were grown at 1150 ºC and 40 torr.

High resolution X-ray (0002) and (1012) spectra were then measured and the off-axis FWHM values were found to be 90 arc-sec and 56 arc-sec for the n^{++}-AlGaN and the AlN layers respectively. From the AFM data, the RMS roughness was found to be ~0.32 nm for a (2µm × 2µm) scan.

To study the high-field performance of the PMOCVD AlN layer, circular MESA geometry quasi-vertical conduction Schottky barrier diodes were fabricated using standard photolithography and reactive ion etching (RIE) processes. The n-ohmic contacts Zr/Al/Mo/Au (150/1000/400/300Å) were annealed at 950 ºC in a nitrogen ambient for 30 seconds. The Schottky contact metals Ni (100 nm)/ Au (200 nm) nm were deposited using e-beam evaporation.

For a 30 µm diameter un-passivated Schottky barrier diode on the PMOCVD n-AlN layer, a reverse breakdown voltage V_{BD}=396V was measured. This translates to a breakdown field of ~9.9 MV/cm. At a forward bias of 20V we measured a current density of 2.68 kA/cm^2. The ideality factor for our devices was also measured to be 1.8. From a linear plot of the I-V characteristics, device turn-on voltage was found to be approximately 2.2 Volts. Our study thus demonstrates the viability of the PMOCVD growth and doping approach to yield *n*-AlN layers suitable for high current-high voltage devices.

ED-Fri-B5* - Unified explanation of bias dependence of threshold voltage shift under positive bias stress in GaN planer MOSFETs with SiO2 gate dielectric

4. Electronic devices

Yuki Ichikawa[1]
Katsunori Ueno[2], Tsurugi Kondo[2], Ryo Tanaka[2], Shinya Takashima[2], Jun Suda[3]
[1] Nagoya Univesity, Nagoya, Aichi , Japan
[2] Fuji Electric Co., Ltd., Tokyo, Japan
[3] Nagoya Univesity, Nagoya, Aichi , Japan, Institute of Materials and Systems for Sustainability, Nagoya University, Aichi

Abstract text: Suppression of threshold voltage (V_{TH}) instability is a crucial issue in GaN vertical power MOSFETs. We investigated V_{TH}instability using a GaN lateral planar-gate MOSFET, a key component of vertical power DMOSFETs. In our previous study,[1] stress-time and bias dependence suggested that electrons were trapped in near-interface traps (NIT) via tunneling. Therefore, we performed a theoretical analysis of V_{TH} shift with a simple model of electron tunneling to trap states. However, the bias dependence of the V_{TH} shift could not be reproduced. In this study, we modified the tunneling model by taking into account the thermal excitation of electrons and the energy distribution of NIT. Using common parameters, our modified model successfully provided a unified explanation for the bias dependence of V_{TH} shift at room temperature. Based on the agreement between the experimental and analytical results, we obtained important information on the trap density (N_T), the energy level of NIT, and other parameters. We also performed an analysis of the bias dependence of V_{TH} shift at various temperatures using the proposed model to elucidate the mechanism.

Gate dielectric (100 nm SiO_2) was deposited on homoepitaxial p-type GaN (0001) via remote-plasma-assisted CVD. Source and drain regions were formed through Si-ion implantation followed by activation annealing. To investigate the effect of stress bias over time, the application of bias stress and transfer characteristic measurements were conducted repeatedly for a total duration of 6000 seconds. These measurements were carried out under different gate bias voltages and at various temperatures.

The amount of V_{TH} shift increased with increasing stress duration and bias voltage. A trap energy level of E_C + 0.78 eV and N_T of 2-8.5 $\times 10^{12}$ cm^{-3} were obtained using the modified tunneling model. Additionally, we successfully reproduced the bias dependence at each temperature by varying only the trap density N_T. N_T was found to increase with rising temperature. Furthermore, we confirmed that V_{TH} shift behavior at room temperature was restored after high-temperature stress, suggesting N_T is not permanently increased by high-temperature bias stress.

This work was supported by MEXT-Program for Creation of Innovative Core Technology for Power Electronics Grant Number JPJ009777.

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Novel Nitrides with Sc

2025-07-11
08:30 - 10:00
Novel Nitrides with Sc

GR-Fri-1* - Indium Surfactant Assisted Molecular Beam Epitaxy Growth of AlScN

1. Growth

Pierce Lonergan[1]
Thai-Son Nguyen[2], Chandrashekhar Savant[2], Henryk Turski[3], Huili (Grace) Xing[4], Debdeep Jena[4]
[1] Department of Electrical Engineering and Computer Engineering, Cornell University, Ithaca NY, USA
[2] Department of Materials Science and Engineering, Cornell University, Ithaca NY, USA
[3] Institute of High Pressure Physics, Polish Academy of Sciences, Sokołowska 29/37, Warsaw, 01-142, Poland
[4] Department of Electrical Engineering and Computer Engineering, Department of Materials Science and Engineering, Kavli Institute for Nanoscale Science, Cornell University, Ithaca NY, USA

Abstract text: AlScN is a promising material for electronics and photonics due to its high piezoelectricity and ferroelectricity[1-3]. N-rich growth necessary to avoid intermetallics during AlScN growth results in 3D islands with rough surfaces[4-5]. In surfactant is known to promote 2D step flow growth of AlGaN[6]. Considering the preference of nitrogen to bond to Al and Sc over In, we evaluate here if indium is a suitable surfactant in AlScN growth.

AlScN films were grown on UID GaN with varying In flux from 0 to 5×10^{-7} Torr. Excess Ga droplets after GaN growth were consumed to avoid Ga incorporation in AlScN. Without In, AlScN films showed a 3D island growth with pits. With In, the underlying GaN morphology was reproduced on AlScN surface with 0.45 nm RMS. EDAX and XPS confirmed that In acts as surfactant without getting incorporated in the AlScN for all samples except the highest flux sample.

The AlScN films grown from 450-750 °C preserved underlying GaN morphology and showed atomically smooth surfaces. Indium incorporation at <650 °C was confirmed by XRD 002 peak shift, increased In incorporation, an growth rate. We report In surfactant-based growth without undesirable rock-salt, intermetallic phases. Lastly, XRD rocking curve FWHM indicates that the overall crystal quality of the quaternary alloy AlScInN is similar to that of AlScN with In surfactant. To investigate the valid range for the use of In as a surfactant, an In desorption curve was calculated and the measured thermocouple temperature was calibrated using a known desorption curve for GaN[7]. This confirms the observed results with In incorporating in the 450-550 °C from the temperature series as well as the 5×10^{-7} Torr sample.

In surfactant assisted AlScN film growth in the In-desorption regime (T > 550 °C, In flux < 5.0×10^{-7} Torr) showed improved morphology without In incorporation. This growth regime is compatible with most AlScN epitaxial heterostructures with other III-nitrides such as AlN and GaN[4], providing a new pathway to the crystalline AlScN with robust surface quality.

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GR-Fri-2 - Sputter Epitaxy of ScAlN Films on MOCVD-Grown GaN HEMT Structures

1. Growth

Atsushi Kobayashi[1]
Tomoya Okuda[1], Shunsuke Ota[1], Takahiko Kawahara[2], Kozo Makiyama[2], Ken Nakata[2], Kouei Kubota[3], Yusuke Wakamoto[3], Takuya Maeda[3]
[1] Department of Materials Science and Technology, Tokyo University of Science, Tokyo, Japan
[2] Transmission Devices Laboratory, Sumitomo Electric Industries Ltd., Yokohama, Japan
[3] Department of Electrical Engineering and Information Systems, The University of Tokyo, Tokyo, Japan

Abstract text: Recently, wurtzite-type nitrides, represented as *X*AlN (*X* = Sc, Y, B), have attracted significant attention as promising barrier layer materials for GaN high electron mobility transistors (HEMTs). Among them, ScAlN has been extensively studied due to its unique ferroelectricity and significant spontaneous polarization. It has been reported that ScAlN with a certain Sc composition can be lattice-matched to GaN. However, the impact of ScAlN growth conditions on its structural and electrical properties remains unclear. In this study, we explore the sputter epitaxy of ScAlN films on AlGaN/AlN/GaN HEMT structures grown by MOCVD, focusing on their structural and electrical characteristics.

We grew ScAlN films (~20 nm) with Sc compositions ranging from 5% to 20% on $Al_{0.2}Ga_{0.8}N$ (~3 nm)/AlN (~1 nm)/GaN/SiC templates via sputtering.[1-3)] The growth temperatures for ScAlN ranged from 250 to 800 °C. Some samples were annealed at temperatures higher than their respective growth temperatures. Structural characterization was conducted using high-resolution X-ray diffraction (XRD), reciprocal space mapping (RSM), atomic force microscopy (AFM), and scanning transmission electron microscopy. Hall effect measurements were performed to evaluate the electrical properties of the ScAlN/AlGaN/AlN/GaN heterostructures.

We performed the XRD $2\theta/\omega$ scans of ScAlN/AlGaN/AlN/GaN heterostructures with various Sc compositions. A systematic shift in the ScAlN 0002 diffraction peak toward lower angles was observed with increasing Sc composition, indicating an increase in the *c*-axis lattice constant. RSM measurements around the 10-15 diffraction, showing vertically aligned reciprocal points, confirm the coherent growth of ScAlN on the GaN HEMT structures. The Hall effect measurements demonstrated that the sheet electron density (n_s) and electron mobility of a $Sc_{0.06}Al_{0.94}N/Al_{0.2}Ga_{0.8}N$/AlN/GaN structure were 1.4×10^{13} cm^{-2} and 1332 cm^2 V^{-1} s^{-1}. The n_s of this structure was higher than that of the HEMT structure without the ScAlN layer. These results indicate that the ScAlN epitaxially grown by sputtering remotely induces additional electrons at the AlN/GaN interface.

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GR-Fri-3 - Impact of strain on thermoelectric properties of ScN films grown by high-power impulse magnetron sputtering

1. Growth

Arnaud Le Febvrier[1]
Sanath Kumar Honnali[1], Charlotte Poterie[2], Tiago Fernandes Fernandes[1], Fabien Giovanelli[3], Jean Francois Barbot[2], Per Eklund[1]
[1] Inorganic Chemistry, Department of Chemistry – Ångström Laboratory, Uppsala University, Uppsala, Sweden
[2] Institut Pprime, University of Poitiers, Poitiers, France
[3] Laboratoire GREMAN, CNRS, Université de Tours, Blois, France

Abstract text: Scandium nitride (ScN) is a cubic NaCl-structured, degenerated narrow-bandgap n-type semiconductor with an indirect bandgap of ~0.9 eV and a direct band gap estimated at around 2.6 eV. It has remarkable semiconducting phonon-polariton application, electrical, and piezoelectric application. The physical properties of ScN nitride are sensitive to defects such as crystal defect, morphology, intentional or unintentional doping. In this work, the impact of strain on the electrical transport properties and optical properties has been investigated. With the purpose of reducing the deposition temperature of ScN, High power impulse magnetron sputtering (HIPIMS) technique was used to produce a series of film on c-sapphire in a 250-850 °C temperature range. The composition and overall crystal structure of the film remained relatively the same in the sample series while its optical and electrical properties were deteriorated upon temperature decrease. Using in depth XRD, optical and electrical characterization, the effect of strain and dislocation on the semiconductor properties of ScN was evaluated. A reduction of deposition temperature from 850 °C to 450 °C yield a slow degradation of the electrical, and optical properties to a drastic change for a film deposited below 450 °C. Below 450 °C, the films present a high dislocation density (10^{11} m^{-2}) along with a rhombohedral distortion of ScN cell (α: 90° → 88.6°) being the main cause of electrical transport deterioration (σ/10000; n/100, μ/100). The presence of dislocation / crystal defect in the film creates defect states near the valence and conduction bands which impact the electron density, hence their correlated electrical transport and thermoelectric properties. To the best the ScN shows promising thermoelectric properties with its natural orange appearance when grown at high temperatures while behaving like a poor semiconductor with a black appearance when grown at low temperature.

GR-Fre-4 - Optimization of the interfaces of ScAlN/GaN HEMTs grown by ammonia-source MBE for high-power high-frequency applications

1. Growth

Yvon Cordier[1]
Florian Bartoli[1], Aimeric Courville[1], Valentina Gallardo Mödinger[1], Ileana Florea[1], Philippe Vennéguès[1], Maxime Hugues[1]
[1] Université Côte d'Azur, CNRS, CRHEA

Abstract text: ScAlN is a promising barrier layer for high electron mobility transistors (HEMTs) in view of power switching and RF/mm-wave power amplifier applications. The development of the epitaxy of this alloy has started with plasma-assisted molecular beam epitaxy (MBE), followed by metal organic vapor phase epitaxy (MOVPE). More recently, we have demonstrated the growth with ammonia-source MBE under nitrogen-rich regime of $Sc_xAl_{1-x}N$ barriers quasi-lattice matched with GaN (x~14%) [1]. The advantages of this growth regime in terms of control of growth rate, alloy composition and homogeneity [2] have been demonstrated and functional transistors have been fabricated on heterostructures grown on Silicon [3] and GaN-on-Sapphire templates. However, the surface of ScAlN rapidly oxidizes and suffers a lack of stability during the device process. For this reason, in-situ grown cap layers such as AlN, GaN and their combination have been investigated. Furthermore, the electron mobility in the 2-dimensional electron gas (2DEG) generated at the interface between the barrier and the GaN channel is highly sensitive to the confinement of carriers and the AlN exclusion layer intercalated between ScAlN and GaN plays a major role. According to Hall effect measurements, the room-temperature electron mobility in the 2DEG (populated with 2-$4x10^{13}$ electrons/cm²) of most of the samples we have grown ranges from 500 to about 1000 cm²/V.s depending on the quality of the interface which features a 1-2 nm AlN exclusion layer. The typical 2DEG sheet resistances range between 240 and 300 Ohm/sq. In absence of the AlN exclusion layer, the resistance rises to 785 ohm/sq. Furthermore, optimizations of the growth of the AlN exclusion layer within a 10 nm barrier HEMT structure lead to a sheet resistance of 210 ohm/sq, a promising result for the fabrication of high-performance transistors adapted for RF applications.

This work is partly supported by the French technology facility network RENATECH, the National Research Agency (ANR) through the 'Investissements d'Avenir' program GaNeX (ANR-11-LABX-0014) and the project TWINS (ANR-23-CE51-0011) as well as ECSEL JU project GaN4AP under Grant Agreement No. 101007310.

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GR-Fri-5 - Self-organised ordering of scandium into monolayers of aluminum nitride and its implication for materials growth and AlScN based semiconductor devices

1. Growth

Ulrich Bläß[1]
Mingjian Wu[2], Boris Epelbaun[1], Elke Meissner[3], Sven Besendörfer[1]
[1] Fraunhofer Institute for Integrated Systems and Device Technology (IISB), Erlangen, Germany.
[2] Friedrich-Alexander-Universität Erlangen-Nürnberg (IMN), Erlangen, Germany.
[3] Fraunhofer Institute for Integrated Systems and Device Technology (IISB), Erlangen, Germany.
Friedrich-Alexander-Universität Erlangen-Nürnberg (LEB), Erlangen, Germany.

Abstract text: Within the last decade, scandium (Sc) bearing aluminium nitride (AlN) increasingly appears as a promising material for next generation of semiconductor devices. This is due to a 4-5 times higher piezoelectric response, compared to pure AlN [1]. The enhanced piezoelectric response led e.g. to a high 2D electron gas concentration in high-electron mobility transistors enabling high efficiencies and switching frequencies, which are essential parameters e.g. for power electronic applications and others.

All these $Al_{1-x}Sc_xN$ thin films with x up to 0.4 are considered being thermodynamically metastable due to a huge miscibility gap between AlN and ScN, even substrate misfit strain may stabilise their existence [2].

In this study we demonstrate that excessive annealing between 1400° and 1700°C led to a new kind of Sc-ordering [3]. Scanning transmission electron microscope (STEM) investigations reveal at atomic resolution that a self-organised ordering process led to a complete ordering of Sc-atoms into basal monolayers, which are recurring statistically every 5 to 8 layers. Inside these layers, Sc-atoms change their coordination from former tetrahedral in disordered AlN wurtzite structure to octahedral in these layers. This local equilibration of Sc-atoms is assumed as driving force for the formation of the layered phase. Whether this is triggered by a high oxygen content present in these layers, is discussed. In between these layers, Sc-free AlN occurs in the wurtzite structure. The sequence of atomic positions along the hexagonal *c*-direction is strictly ordered, except the statistic recurrence of Sc-layers. Thermo-dynamically these Sc-rich layers are interpreted as exsolution lamellae of minimal atomic width, for which tiny nuclei has been first observed at 1400°C.

This study demonstrates that the metastable existence of disordered AlScN of wurtzite structure is limited in temperature relatively close to e.g. MOVPE process temperatures. To obtain excellent material for electronic devices, the growth temperature should be sufficiently high to gain good quality instantaneously, but below the onset of significant diffusion to prevent structural degradation.

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Plenary 5

2025-07-11
10:30 - 11:10
Plenary 5

AlN – The Extreme Bandgap Semiconductor

1. Growth

C.E. Quiñones[1]
D. Khachariya[1], S. Mita[1], P. Reddy[1], R. Kirste[1], S. Pavlidis[1], R. Collazo[1], **Zlatko Sitar**[1]
[1] North Carolina State University, Material Science and Engineering, Raleigh, NC, USA & Adroit Materials, Inc., Cary, NC, USA.

Abstract text: AlN is an extreme bandgap material (E_g = 6.1 eV) that can potentially revolutionize not just UV and VUV optoelectronics but also high-power, high-frequency electronics. Although most challenges in crystal growth and epitaxy of AlN have been overcome, achieving controlled electrical conductivity of technological interest has proven to be challenging. While controlling the chemical and electrochemical potentials during doping has been crucial for achieving doping and compensation control, the obtained conductivity was still modest. The presumed DX^{-1} formation has been considered an insurmountable killer defect as it pins the Fermi level and imposes a technologically unimpressive limit on the achievable free carrier concentration. We have developed several novel equilibrium and non-equilibrium approaches for doping and point defect management in AlN and have shown that donors in AlN do not undergo a DX^{-1} transition but rather are distributed between a shallow and deep state. The shallow state can be kinetically stabilized to obtain highly-conducting n-type AlN with carrier concentrations in the mid-10^{18} cm^{-3} range and mobilities approaching 400 cm^2/Vs. These results have enabled the first demonstration of AlN Schottky diodes capable of >5 $kAcm^{-2}$ with a critical breakdown field exceeding 12 $MVcm^{-1}$ and stable operation up to 700°C.

Plenary 6

2025-07-11
11:10 - 11:50
Plenary 6

Nitride micro-LEDs for Digital Light

3. Optical devices

Ulrich Steegmüller[1]
[1] ams OSRAM, Regensburg, Germany

Abstract text: Over the recent years, µ-LEDs with lateral sizes below 50 µm got much interest from various scientific and commercial institutions. Especially the idea of using LEDs for self-emitting displays got much attention.

Ams OSRAM is actively working on InGaN µ-LEDs for different display applications that will be discussed in this talk. Besides the area of displays, we will give an overview of other potential applications depending on the laterals pixel size and discuss the different technological challenges coming with smaller chip sizes. Besides the well-known basic physics related problem of decreasing efficiency there are also severe challenges regarding the large-scale manufacturing of such tiny LEDs.

The combination of arrays of very small µLEDs with a field of driving circuits by a structured bondlayer has been developed and commercialized by ams OSRAM as a groundbreakingtechnology. The principle allows for controlling each µ-LED pixel individually based on digital data provided to the driver array. It is therefore called the “Digital Light”.

We will present and discuss different applications of the Digital Light and the respective challenges. In the field of automotive exterior lighting it already found its way into commercial products. But since it is a basis technology there are many more future applications like augmented reality (AR), short-range optical data communication and neuromorphic networks. The significance of the Digital Light technology in existing and future products that make our lives more safe and more comfortable was recognized by the German Future Award for researchers of ams OSRAM and Fraunhofer IZM in 2024.

Plenary 7

2025-07-11
13:10 - 13:50
Plenary 7

Developments and Prospects of GaN-based VCSELs

3. Optical devices

Tetsuya Takeuchi[1]
[1] Meijo University, Nagoya, Japan

Abstract text: GaN-based visible vertical-cavity surface-emitting lasers (VCSELs) are expected to be used as novel light sources in retinal scanning displays, adaptive headlights, visible light communication systems, and point-of-care testing devices. The first room temperature (RT) continuous wave (CW) operation of the GaN-based VCSEL was reported in 2008, with a light output power (LOP) of 0.14 mW at a wavelength of 414 nm. Since then, many research and development efforts have been made, resulting in the demonstration of a wall-plug efficiency (WPE) over 20% in GaN-based VCSELs of 400-450 nm wavelength range, and the demonstration of green VCSELs under RT CW operation.

This presentation will review the research and development history of GaN-based VCSELs in terms of WPE and operating wavelength. A comparison will also be made with GaAs-based infrared VCSELs that have already been commercialized, highlighting the differences between the GaN-based and GaAs-based VCSEL structures. For example, while top and bottom semiconductor-based distributed Bragg reflectors (DBRs) are commonly used in GaAs-based VCSELs, the choice of bottom DBRs, semiconductor-based or dielectric-based, is still controversial in GaN-based VCSELs. In addition, a perfect lateral optical/current confinement structure formed by a lateral selective oxidation in GaAs-based VCSELs cannot be adopted in GaN-based VCSELs.

Next, the developments towards higher WPE at Meijo University are described, including three key technologies, such as high quality AlInN/GaN DBRs, nano-height mesa for lateral optical/current confinement, and in-situ cavity length control. Using a combination of the above three technologies, our GaN-based VCSELs have demonstrated a LOP of 15 mW and a WPE of 26% at 420 nm under RT CW operation. Finally, the future prospects of the GaN-based VCSEL developments are discussed.

Plenary 8

2025-07-11
13:50 - 14:30
Plenary 8

III-Nitride Electronics in the Era of Artificial Intelligence

4. Electronic devices

Patrick Darmawi-Iskandar[1]
Deniz Erus[1], Ashley Goodnight[1], Jung-Han Hsia[1], John Niroula[1], Minsik Oh[1], Hridibrata Pal[1], Joshua Park[1], Joshua Perozek[1], Aditya Varma[1], Pradyot Yadav[1], **Tomás Palacios**[1]
[1] Microsystems Technology Laboratory Massachusetts Institute of Technology, Cambridge, Massachusetts

Abstract text: Microelectronics is quickly becoming a trillion dollar industry and its strategic importance for modern society is driving governments worldwide to increase R&D efforts and make its supply chain more resilient. At the core of this industry is a growing need for more efficient and flexible power management solutions. Just in the same way that silicon is an almost perfect material for information processing, GaN is an ideal material for energy processing and its importance is quickly growing with the increase of power consumption by electronic systems and, more specifically, data centers [1].

This paper will describe some of the many new opportunities that III-Nitride electronics has to enable key building blocks of future artificial intelligence (AI) data centers. Although modern data centers consume as much energy as it can be generated by a nuclear power plant, approximately 30 to 40% of that energy never reaches the CPU's and GPU's. It is either dissipated as heat in the power converters that reduce the grid-level voltages down to the 0.7-1.1V typical in highly scaled Si chips, or used to remove the dissipated hear. These power converters can benefit tremendously from recent developments in vertical GaN transistors, which by increasing the voltage swing in the converter, can potentially reduce the number of conversion stages and increase efficiency significantly. These medium voltage converters, however, suffer from electromagnetic interference (EMI) and difficult gate driver circuits. A GaN optically-controlled device could significantly improve their performance [2].

A second type of novel GaN power switches is needed at the interposer and CPU/GPU level. Approximately 30% of the electrical power in the interposer never reaches active transistors. It is lost as Joule dissipation in the interconnects due to the extremely large current levels induced by the low operating voltages of modern microelectronic chips. To fix this problem, distributed networks of power management circuits with very high power density levels need to be embedded in both future interposers [3] and the back-end-of-the-line (BEOL) of Si chips. III-Nitrides are, again, ideal for many of these circuits, however they need to be optimized for operation at very low voltages (<10 V) [4]. This talk will describe these new transistors, as well as an outlook for their heterogeneous integration with Si.

Acknowledgements: This work was supported in part by the SUPREME and CHIMES centers in JUMP 2.0, a Semiconductor Research Corporation (SRC) program sponsored by Defense Advanced Research Projects Agency (DARPA) under the award no. 145105-21913.The authors would also like to acknowledge the partial support of the Air Force Office of Scientific Research (Dr. Ken Goretta) and the Office of Naval Research (Cpt. Lynn Petersen).

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Poster

Poster Session 1

2025-07-07
17:00 - 19:00
Poster Session 1

GR-Mon-P1 - Convective Transport and Supersaturation Distribution in Ammonothermal GaN Crystallization: A CFD Analysis

1. Growth

Marek Zak[1]
Pawel Kempisty[1], Boleslaw Lucznik[1], Robert Kucharski[1], Mikolaj Amilusik[1], Arkadiusz Puchalski[1], **Michal Bockowski**[1]
[1] Institute of High Pressure Physics "Unipress", PAS

Abstract text: Gallium nitride (GaN) substrates of high structural quality are essential for next-generation electronic and optoelectronic devices. One promising technology for crystallizing bulk GaN is the ammonothermal method. This method dissolves polycrystalline GaN (feedstock) in supercritical ammonia in one zone of an autoclave and transports it to a second zone where the solution becomes supersaturated and GaN crystallizes. A proper temperature gradient between the zones enables convective mass transport. However, due to technological limitations (tightly closed reactors) and extreme conditions (chemically aggressive environment and high ammonia pressure), direct monitoring of the reactor processes in ammonothermal growth experiments is challenging. Autoclaves act as “black boxes” with temperature measured externally. A detailed analysis of convective transport can deepen our understanding of the ammonothermal crystal growth process, thereby accelerating its further development.

In this work, we examine convective transport in a three-dimensional (3D) approximation within an ammonia-based supercritical solution during GaN crystallization. The Computational Fluid Dynamics (CFD) method was employed to model the processes inside large-volume autoclaves using a time-dependent set of Navier-Stokes equations with a k-ω turbulence model. Solving these equations enabled us to determine flow velocity, temperature, and GaN supersaturation inside the growth zone. Supersaturation computation is based on recent solubility results by Grabianska et al. [1]. The model geometry and boundary conditions were derived from the operating conditions—such as temperature and pressure—of the autoclaves. We used ANSYS Academic engineering simulation software for our simulations. The fluid was modeled as a mixture of ammonia, hydrogen, and Ga spieces. Experimental data were utilized to verify the modeling results. We investigated structural quality, growth rate, and uniformity, relating them to the computational model. Additionally, mass transport through baffle openings was connected to the experimental crystal growth ratio, and the order of magnitude of diffusion coefficients was estimated to help with future quantitative modeling of growth ratios and new installation geometries.

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GR-Mon-P2 - 3D CFD Investigation of the Effects of Baffle Geometry and Autoclave Size on Convective Transport and GaN Crystal Growth in Ammonothermal Processes

1. Growth
Marek Zak[1]
Pawel Kempisty[1], Boleslaw Lucznik[1], Robert Kucharski[1], **Michal Bockowski**[1]
[1] Institute of High Pressure Physics "Unipress", PAS

Abstract text: High-quality gallium nitride (GaN) substrates are essential for developing the next generation of electronic and optoelectronic devices. One of the most promising methods for bulk GaN crystallization is the ammonothermal technique. This process involves dissolving polycrystalline GaN in supercritical ammonia within one zone of an autoclave and then transporting it to another zone, where the solution becomes supersaturated, leading to GaN crystallization. A controlled temperature gradient between these zones enables convective mass transport. Due to technological constraints (hermetically sealed reactors) and extreme conditions (a chemically aggressive environment and high ammonia pressure), direct observation of the processes inside ammonothermal reactors is challenging. The autoclaves function as "black boxes," with their operation monitored primarily through external temperature measurements. A detailed analysis of convective transport can provide deeper insights into the ammonothermal crystal growth process, facilitating faster, more efficient advancements in this technology.

In this work, we examine convective transport in a three-dimensional (3D) approximation within an ammonia-based supercritical solution during the crystallization of GaN. The Computational Fluid Dynamics (CFD) method was employed to model processes inside large-volume autoclaves. A time-dependent set of Navier-Stokes equations with k-ω turbulence model was used. Solving these equations allowed us to determine the flow velocity and temperature. The model geometry and boundary conditions were determined based on the operating conditions, such as temperature and pressure, of the working autoclaves. We used ANSYS Academic engineering simulation software for our simulations. Different autoclave sizes, baffle geometries and internal installations are compared in this study. Both computational and experimental results are used to show fluid mixing between dissolution and growth zone. Goal is to deepen understanding of the process and simulation methodology towards further optimization of growth ratio and structural quality of the crystals.

GR-Mon-P3 - Evolution of V-Pits in GaN Grown by Na flux Method

1. Growth

Tao Zhang[1]
Zongliang Liu[2], Zhiwei Si[3], Xiaohui Peng[1], Xiaoming Dong[1], Ning Tang[1], Ke Xu[1]
[1] Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, Suzhou, Jiangsu, China
[2] Shenyang National Laboratory for Materials Science, Jiangsu Institute of Advanced Semiconductors, Suzhou, Jiangsu, China
[3] Information Materials Research Department, Suzhou Laboratory, Suzhou, Jiangsu, China

Abstract text: V-pit defects significantly influence the crystal growth kinetics and optoelectronic properties of GaN materials, yet their evolutionary behavior in Na flux-grown GaN remains insufficiently explored. This study systematically investigates the evolution of V-pit defects through cathodoluminescence (CL) mapping coupled with transmission electron microscopy (TEM) characterization. CL results reveal that the lateral expansion of V-pits is governed by the anisotropic growth of (10-11) planes, which simultaneously promotes the incorporation of elevated concentrations of shallow donor impurities. Intriguingly, the subsequent dominance of (11-2m) plane growth initiates a progressive annihilation process of these defects. TEM analysis further identifies that the nucleation of V-pits originates from mixed-type dislocations (a+c type) within the GaN lattice. These findings provide critical insights into defect engineering strategies for optimizing Na-flux GaN crystal growth.

GR-Mon-P4* - Extremely small trap concentrations in quartz-free hydride vapor phase epitaxy-grown n-type GaN confirmed by capacitance transient spectroscopy

1. Growth

Yusuke Hirayama[1]
Masahiro Horita[2], Jun Suda[2], Shota Kaneki[3], Hajime Fujikura[3]
[1] Nagoya University, Nagoya, Aichi, Japan
[2] Nagoya University, Nagoya, Aichi, Japan; Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Aichi, Japan
[3] Sumitomo Chemical Corporation, Hitachi, Ibaraki, Japan

Abstract text: To realize GaN vertical power devices, it is necessary to use lightly doped, thick n-type layers that are free of impurities such as carbon (C) and iron (Fe). The hydride vapor phase epitaxy (HVPE) method is well suited for this purpose because it offers a high growth rate and uses source materials that do not contain C. However, the conventional HVPE method suffers from high background doping of silicon (Si) and oxygen (O) originating from quartz components. Fujikura *et al*. reported that the quartz-free HVPE (QF-HVPE) method—achieved by removing quartz components from the growth reactor—drastically reduces the background donor concentrations [1]. Detailed characterizations were performed [2], confirming reduced concentrations of residual impurities such as C and Fe.

Recently, we installed a new, well-designed, mass-production-oriented growth reactor that enables GaN-on-GaN epitaxy with higher material purity, improved uniformity, and larger wafer sizes (up to 6 inches). For GaN homoepitaxial layers grown by this new reactor, the concentrations of C and Fe impurities are reduced below the detection limit of secondary-ion mass spectrometry (SIMS). In this paper, we performed deep-level transient spectroscopy (DLTS) and optical isothermal capacitance transient spectroscopy (OICTS) to determine trap concentrations originating from impurities. Our measurements revealed that the H1 hole trap concentration (corresponding to C) is 1.2×10^{13} cm^{-3}, and the E3 electron trap concentration (corresponding to Fe) is 5.2×10^{12} cm^{-3}. These values are far below the SIMS detection limits. Typical n-type doping concentrations for vertical power devices range from 5×10^{15} to 2×10^{16} cm^{-3}, making the C and Fe impurity levels—two to three orders of magnitude lower—negligible for device performance. The net donor concentration of the sample is 4.7×10^{14} cm^{-3}, which is nearly equal to the Si concentration measured by SIMS after subtracting the H1 and E3 acceptor-type trap contributions, suggesting that no other impurities or intrinsic point defects are present.

A part of this paper is based on results obtained from a project, JPNP21005, subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

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[2] Kanegae, *et al.*, *Appl. Phys. Lett.* **115**, 012103 (2019).

GR-Mon-P5* - Fabricating Damage-Free Surface for Crystal Growth on Seed GaN Crystal Grown by Na-flux Method Using PEC Etching with Bias Voltage Application

1. Growth

Tatsuya Fukagawa[1]
Kiyoto Kayao[1], Daisetsu Toh[1], Jumpei Yamada[1], Masayuki Imanishi[1], Shogo Washida[1], Shigeyoshi Usami[1], Yusuke Mori[1], Yasuhisa Sano[1]
[1] The University of Osaka, Suita, Osaka, Japan

Abstract text: Using a GaN crystal grown by the Na-flux method (referred to as "Na-flux GaN") as a seed crystal leads to a bulk GaN crystal with low dislocation density. Slicing the bulk crystal can produce GaN substrates with low dislocation density. Additionally, reusing a Na-flux GaN as the seed crystal is proposed to reduce the cost of the GaN substrate, as it takes a long time to grow Na-flux GaN. However, the slicing process introduces a damaged layer on the surface of the Na-flux GaN. As the crystallographic defects in the damaged layer of the seed crystal propagate to the growth layer, the damaged layer must be removed. Conventionally, lapping and subsequent chemical mechanical polishing (CMP) are used to remove the damaged layer. However, because the CMP process involves mechanical removal, it is difficult to eliminate the damaged layer efficiently, resulting in a time-consuming process that requires more than 30 hours. We propose to remove the damaged layer using photoelectrochemical (PEC) etching. In PEC etching, the GaN surface is efficiently oxidized with holes generated by UV light irradiation in an etchant, such as an acidic or alkaline solution, and the etchant dissolves the oxide. The damaged layer promotes the recombination of electron-hole pairs, making it difficult for PEC etching to remove the damaged layer [1]. To prevent this recombination, we considered applying a bias voltage to the GaN substrate. In this study, we removed the damaged layer induced by the lapping process using PEC etching under the bias voltage application.

The sample was a Na-flux GaN crystal lapped with diamond abrasives, with a damaged layer thickness of 3 μm. PEC etching at a bias voltage of 3 V successfully removed the damaged layer completely within 45 minutes, which is a 40-fold improvement over the CMP process.

Subsequently, we grew GaN using the Na-flux method on the partially PEC-etched Na-flux GaN. We then evaluated the crystallinity of the growth layer on the etched and unetched areas using multiphoton photoluminescence. The dislocation density in the growth layer on the etched area was significantly lower than that on the unetched area. These results indicate that our method is promising for removing the damaged layer efficiently after the lapping process and preparing the seed GaN crystals.

Reference

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GR-Mon-P6 - Fabrication and Characterization of 4-Inch GaN Single Crystal Substrate

1. Growth

Yongzhong Wu[1]
Baoguo Zhang[1], Haixiao Hu[1], Yongliang Shao[1], Xiaopeng Hao[1]
[1] School of Materials Science and Engineering, Qilu University of Technology, Jinan, P. R. China.

Abstract text: Hydride Vapor Phase Epitaxy (HVPE) is the primary method for growing large-sized free-standing gallium nitride (GaN) single crystals. It is favored for its simple equipment setup, rapid growth rate, and cost-effectiveness. In this study, we employed MOCVD-GaN/Al_2O_3 (MGA) as a substrate for HVPE growth and successfully obtained a 7 mm-thick free-standing GaN single crystal. A 4-inch GaN single crystal substrate was then prepared through cutting, surface grinding, and polishing. The structural quality of the GaN crystal was characterized by X-ray diffraction (XRD), showing a full width at half maximum (FWHM) of 74 arcsec for the (102) peak. Cathodoluminescence (CL) spectroscopy revealed a dislocation density of $1.3*10^6$ cm^{-2}. The electrical properties of the wafers were evaluated by measuring the sheet resistance using the eddy current method, and the resistance distribution across different wafers was analyzed to assess uniformity. These results provide a solid foundation for further optimization of GaN single crystal growth and the regulation of its conductive properties.

Figure 1. (a) Wafer resistance contour plot. (b) Wafer resistance mapping. (c) 4-inch GaN substrate. (d) CL spectroscopy.

GR-Mon-P7 - GaN catalyzed nucleation of low threading dislocation GaN on sapphire

1. Growth

Ashutosh Kumar[1]
Qin Wang[2], **Peter Ramvall**[1]
[1] RISE Research Institutes of Sweden, Ole Römers Väg 1, SE-223 63 Lund, Sweden
[2] RISE Research Institutes of Sweden, Isafjordsgatan 22, SE-164 40 Kista, Sweden

Abstract text: Sapphire is commonly used as the preferred substrate for LED and occasionally for electronic applications. Especially, in case of semi-vertical high-power MOSFET structures employing thick drift layers, a thin nucleation layer is desirable.

In this work we investigated a method of obtaining a thin GaN nucleation layer on sapphire with similar crystal quality as a regular thicker one. By the presence of a GaN surface during nucleation on sapphire and growth, a substantial improvement of the crystal quality as observed by a narrowing of the x-ray diffraction (XRD) rocking curve (RC) peaks corresponding to symmetric (0002) and asymmetric (10-12) reflections was observed. With this method a GaN layer with a thickness of less than 1 mm having similar quality as the more commonly used thicker, about 3 mm, GaN buffer layer on sapphire was grown.

An Aixtron MOCVD tool was used for the investigation. To evaluate the effect of a GaN surface present during nucleation, the central position and every second position at the perimetry of the susceptor the sapphire substrates were replaced by GaN on sapphire wafers. For comparison, reference growths with sapphire substrates in all positions were also performed.

The nucleation procedure appeared substantially more effective in the presence of the GaN surface as observed by in-situ reflectivity characterization by LayTec EpiTT a steady state growth occurring at an earlier state i.e., when the top and bottom reflection levels are similar for consecutive oscillations.

The material quality of 1 mm thick GaN nucleated with GaN catalyst wafers present was compared with a regular 3 mm thick GaN on sapphire layer by XRD RC of (0002) and (10-12) reflection measurements. The FWHM were found to be 355/451 arcsec and 350/630 arcsec, respectively. The material quality of the thin layer appears improved compared to the thicker one. The narrowing of the FMHM of the asymmetric (10-12) peak suggests a substantial lowering of the density of threading dislocations with GaN catalyst present during nucleation.

The RMS (R_q) roughness, as observed by AFM captured over 3 x 3 mm^2 areas, grown on the one hand for 1 mm GaN with catalyst wafers present, and on the other hand for a regular 3 mm, GaN buffer layer with sapphire only present, were both around 0.2 nm.

GR-Mon-P8 - Hydride Vapor Phase Epitaxy Growth of Freestanding GaN Substrates with High Conductivity for Vertical Power Electronic Devices

1. Growth

Yumin Zhang[1]
Demin Cai[1], Yu Xu[1], Jianfeng Wang[1], **Ke Xu**[1]
[1] Suzhou Nanowin Science and Technology Co., Ltd., Suzhou 215000, P. R. China

Abstract text: The avalanche capability is crucial for high-reliability power electronics devices. However, achieving avalanche breakdown is challenging and necessitates the use of high-quality freestanding GaN substrates as well as sophisticated edge termination designs.

The conductivity of freestanding GaN substrates plays a crucial role in reducing the on-resistance, lowering the specific contact resistivity of ohmic contacts on N-polar surfaces, and enhancing the reliability of ohmic contacts. In this study, freestanding GaN substrates with carrier concentrations in the range from 6.7×10^{17} to 1.7×10^{19} cm^{-3} were grown by hydride vapor phase epitaxy (HVPE). The crystal quality and electrical properties of GaN substrates were characterized. All samples showed no obvious tensile stress regardless of the higher carrier concentration. Moreover, the mobility of freestanding GaN substrates is superior to the GaN template with higher dislocation density at the same carrier concentration. The influence of carrier concentration on the performance of ohmic contact on the N-face of Si-doped GaN is also studied by circular transfer length measurement. The specific contact resistivity decreases monotonically with increase of carrier concentration, while it increases with the annealing temperature. The sample with a carrier concentration of 1.7×10^{19} cm^{-3} still showed ohmic behavior after annealing at 450 °C.

GaN p-i-n diodes were grown on the high-conductivity freestanding GaN substrates. The avalanche characteristics of vertical GaN PIN diodes with N-ion implantation guard rings were investigated. The net carrier concentration in the drift layer is as low as 3.5×10^{15} cm^{-3} measured by C-V test. The guard rings (GRs) was formed on the edge of p-i-n diodes via N-ion implantation, resulting in a significant reduction in reverse leakage current density by over 10^6. By optimization of the GRs, we achieved an enhancement in the device's avalanche breakdown voltage from 759.8 to 864 V. Notably, the devices maintained an avalanche breakdown even at an elevated temperature of 225 °C. The relationship between avalanche voltage and temperature is linear, with a positive temperature coefficient α of approximately 4.42×10^{-4} K^{-1}.

GR-Mon-P9 * - InGaN donor substrate for highly relaxed InGaN pseudo-substrate

1. Growth

Hassan DAMEN[1]
Maud NEMOZ[2], Daniel Pépin FOWAN[2], Benjamin DAMILANO[2], Agnès TRASSOUDAINE[3], Amélie DUSSAIGNE[1]
[1] Univ. Grenoble Alpes, CEA, Leti, F-38000 Grenoble, France
[2] CRHEA/CNRS, F-06560 Valbonne, France
[3] Univ. Clermont Auvergne, IP/CNRS, F-63100, Clermont-Ferrand, France

Abstract text: Virtual and augmented reality are key applications for nitride-based micro-light emitting diodes (micro-LEDs), enabling full color micro-displays with pixel pitches below 10 μm. Achieving RGB pixels on a single substrate relies on a native emission approach using InGaN alloy. High indium content red micro-LEDs suffer from efficiency loss due to material degradation. Enhancing red InGaN-based LED efficiency requires strain reduction, achievable through a relaxed InGaN pseudo-substrate. It can be obtained by porosifying an InGaN donor substrate via the sublimation process and regrowing a top InGaN layer, enabling higher In incorporation while preserving good crystalline quality[1].

This study aimed to optimize the growth parameters of the InGaN donor substrate (InGaN grown on GaN-on-sapphire), as its In content, thickness, and crystalline quality are crucial for the high quality relaxed pseudo-substrate. The ultimate InGaN pseudo-substrate for red emission should comprise a top regrown InGaN layer with a *a* lattice parameter of 3.238 Å, equivalent to bulk .

Key objectives include reducing defect density while maximizing In incorporation. A 50 nm layer with an In content around15% was studied under various growth conditions: lowering growth temperature improves In incorporation but increases defect density, as known; increasing the V/III ratio enhances In incorporation while reducing defect density due to higher active nitrogen availability; high In/Ga ratio for a fixed Ga flow improves In incorporation and reduces In inhomogeneities.

V-pit densities below 2.10^8 cm^{-2} and diameters under 30 nm were measured. Atomic force microscopy (AFM) analysis revealed that higher Ga flow induces the formation of spiral hillocks linked to screw dislocations, while lower Ga flow reduces surface roughness, correlate with a lower localization energy, and thus a more homogeneous InGaN alloy, confirmed by cathodoluminescence (CL) mappings.

An in-plane lattice parameter of 3.205 Å was obtained on a regrown InGaN layer on a porous layer. A 50 nm donor substrate was porosified by the sublimation process. An *a* lattice parameter of 3.230 Å for a relaxation rate of 98% was obtained, already very close to the target. Regrown InGaN layer on top of such highly-relaxed porous layer will be also presented.

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GR-Mon-P10* - Reduction of Threading Dislocations in GaN Crystals During Facet Growth Induced by Oxygen Impurity in the Na Flux Method

1. Growth

Masayuki Imanishi[1]
Kanako Okumura[1], Kosuke Murakami[1], Kosuke Nakamura[1], Keisuke Kakinouchi[1], Kenichi Kawabata[1], Shigeyoshi Usami[1], Masashi Yoshimura[2], Yusuke Mori[1]
[1] Graduate School of Engineering, The University of Osaka University, Japan
[2] Institute of Laser Engineering, The University of Osaka, Japan

Abstract text: High-quality large-diameter GaN substrates are required for the widespread use of vertical GaN-on-GaN devices. We succeeded in fabricating large-diameter GaN substrates with a diameter of φ161 mm using the point-seed technique of the Na flux method [1]. However, the point-seed technique involves a time-consuming growth process; therefore, the growth process must be shortened to improve the productivity of GaN substrates. Thus, we reused once-obtained GaN crystals as native seeds to grow thicker, eliminating the preparation of point-seed substrates and shortening the growth time by more than half [2].

During the regrowth process, facet growth layers are sometimes introduced unintentionally at the interface between the seed and regrowth layers. It was found that the threading dislocation density (TDD) in the layer after facet growth decreased to 10^4 cm^{-2} order, whereas the TDD of the seed crystal was 10^5 cm^{-2} order. We believe that threading dislocations (TDs) accumulate during facet growth and that the TDD is reduced by reactions between TDs and their annihilation. A similar phenomenon was reported for maskless 3D using the hydride vapor phase epitaxy (HVPE) method [3].

We estimated that the facet growth layer was caused by contamination with oxygen impurities, such as the oxidation of Na. Thus, we propose the intentional addition of oxygen through gallium oxide (Ga_2O_3), to induce facet growth, leading to the reduction of the TDD in the GaN crystal. Ga_2O_3 powder was added to the Ga-Na melt at concentrations of 0.005, 0.01, and 0.03 mol%. Based on multiphoton photoluminescence (MPPL) observations, we found that facet growth was successfully induced by the addition of Ga_2O_3, and that the higher the concentration of Ga_2O_3 added, the thicker the facet growth layer became. We also confirmed a reduction in the TDD after facet growth.

The natural change in growth mode from facet to c-plane growth was also an interesting phenomenon. We estimate that this change was caused by the reduction of oxygen impurities in the melt below a certain level owing to the incorporation of oxygen impurities by the crystal itself during facet growth.

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GR-Mon-P11* - Research on the Influence of Vortex Morphology on the Uniformity of Crystal Growth in the Na-flux Method GaN Growth System

1. Growth

Ning Tang[1]
Zongliang LIU[2], Ke XU[2]
[1] Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, Suzhou 215123, Jiangsu, China
[2] Jiangsu Institute of Advanced Semiconductors Ltd, Suzhou 215123, Jiangsu, China

Abstract text: The Na-flux method has exhibited significant potential in the field of gallium nitride (GaN) crystal growth. However, mass transfer in the melt is highly complex, and existing equipment faces challenges in effectively monitoring and regulating the melt environment, posing challenges to controlling the growth rate and thickness uniformity of the crystals. This study employs computational fluid dynamics (CFD) simulations to analyze a two-dimensional axisymmetric model of the crucible and melt. The results reveal the frequent presence of multiple vortices in the melt, whose distribution on the seed crystal surface significantly affects the surface morphology and thickness uniformity of the crystal.

Taking half of the axisymmetric model as an example, when two or more vortices exist on the seed crystal surface, the uniformity of crystal growth is significantly reduced regardless of vortex morphology and trajectory variations. In contrast, when only a single vortex is present on the seed crystal surface, the growth uniformity depends on the projection position of the vortex center along the axial direction. If the projection is located on the seed crystal, the growth rate at the vortex center exhibits a pronounced non-uniform variation, initially decreasing and then increasing near the projection point. Conversely, if the projection does not coincide with the seed crystal, the growth rate remains relatively uniform, with thickness variations depending on the vortex trajectory.

To optimize crystal growth uniformity, this study optimizes process parameters such as the distance between the seed crystal and crucible wall, the inclination angle of the crucible sidewall, and the configuration of the heat source. These adjustments effectively control the position and movement of the vortex center, significantly enhancing the uniformity and quality of crystal growth. This research provides clear control strategies and theoretical guidance for Na-flux method GaN crystal growth.

GR-Mon-P12* - Study of 6-inch HVPE-GaN grown with high growth-rate and thickness-uniformity

1. Growth

XIANGQIAN XIU[1]
WANLI XU[1], YUEWEN LI[1], ZILI XIE[1], DUNJUN CHEN[1], PENG CHEN[1], YOUDOU ZHENG[1], RONG ZHANG[1]
[1] NANJING UNIVERSITY,NANJING,CHINA

Abstract text: Gallium nitride (GaN) is an ideal semiconductor material for the development of microelectronic and optoelectronic devices. high-quality GaN single crystal substrates for homo-epitaxial growth is the fundamental way to achieve high performance of GaN-based devices. Hydride vapor phase epitaxy (HVPE) is currently a most common approach for manufacturing the vast majority of commercially available GaN substrates. Owing to its high growth-rate, how to control the growth of HVPE-GaN with high growth-rate and high uniformity is of great significance for obtaining large-size high quality GaN substrates.

Here, HVPE equipment for 6-inch GaN substrate have been designed and developed independently. The effect of growth conditions such as the distance between source gas and sapphire substrate (D), separator gas, HCl and NH3 carrier gas flow-rates on the thickness-uniformity of as-grown GaN films have been studied with the help of numerical simulation and epitaxy experiments. Simulation and experimental results indicate that the self-developed HVPE system has the characteristics of high growth-rate and high thickness-uniformity. The introduction of separator gas and increasing D can effectively promote the diffusion of GaCl gas to the edge of substrates, so as to significantly improve the thickness-uniformity of the large size epitaxial thick films. By further optimizing the growth conditions, 6-inch GaN film with a thickness of ~ 11 μm achieved thickness nonuniformity about ±1.5% and growth-rate more than 60 μm/ h. The growth-rate increases as the growth time increases. When the growth time is 3 h, the thickness of 6-inch GaN thick film is ~700 μm, the growth rate increases to >200 μm/ h and the thickness-nonuniformity is still in the range of ± 5%. The corrosion effect of non-reactive HCl on the deposited GaN on the quartz tube wall may lead to the increase of GaCl concentration and thus increase the growth rate. The results will help us to design the large-size HVPE growth system and prepare large-area and high quality GaN substrates.

GR-Mon-P13* - The Effect of Ga Composition of Melt on the Dislocation Density at the Coalescence Region of GaN Crystal Grown with the Na-flux Point Seed Technique

1. Growth

Ryotaro Sasaki[1]
Masayuki Imanishi[1], Shogo Washida[1], Kosuke Murakami[1], Shigeyoshi Usami[1], Mihoko Maruyama[1], Masashi Yoshimura[2], Yusuke Mori[1]
[1] Graduate School of Engineering, The University of Osaka, Osaka, Japan
[2] Institute of Laser Engineering, The University of Osaka, Osaka, Japan

Abstract text: For vertical GaN-based power devices, low-threading-dislocation-density (TDD) GaN substrates are required. We have fabricated low-TDD GaN crystals in the Na-flux method using the multi-point seed (MPS) technique, in which tiny GaN crystals are arranged on sapphire. Pyramidal crystals (PC) grow from these seeds and form a rough surface. To flatten the crystal surface, the flux-film-coated (FFC) technique has been invented [1]. By combining these techniques, we grew flat crystals with TDD of mostly 10^3-10^4 cm^{-2}, but high-TDD regions (10^5-10^6 cm^{-2}) exist above the coalescence boundary (CB) of three PCs [2]. Recent studies showed that the FFC technique, which repeatedly immerses and pulls the crystal from Ga-Na melt during growth, reduces TDD at the CB by adjusting the ratio between the growth time inner melt and outer melt to modify the coalescence mode [3]. This study focuses on crystal shape from each seed to further reduce TDD. Previous studies indicate that more uniform crystal shapes lead to lower TDD at the CB [2]. Also, basic studies reported that the uniformity of shapes can be improved by growth in Ga-Na melt at lower Ga composition. Thus, we apply the low Ga composition to the FFC technique to investigate its effect on TDD and crystal shape.
Growth was performed at 870°C, 3.0 MPa under N_2 gas using the MPS substrate. After growing PCs, FFC technique was performed at 880°C. Crystals were grown under conventional (27 mol%) and low Ga composition (19 mol%). The uniformity of crystal coalescence was evaluated by multi-photon excitation photoluminescence (MPPL). The crystal grown at 27 mol% showed an irregular hexagonal shape, while at 19 mol%, it was closer to a regular hexagon. Also, cross-sectional observation showed that in the 27 mol% condition, while most TDs gathered in the CB by propagating at the facet growth sector, some TDs propagated to the surface through the c-plane growth sector. Next, TDD at the CB was evaluated with etch pit density. TDD was 2.5×10^5 cm^{-2} in case of the 27 mol%, while TDD was 1.8×10^5 cm^{-2} in case of the 19 mol%. These results suggest that achieving a uniform crystal shape with low Ga composition reduces generation of TDs during coalescence.
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GR-Mon-P14* - Toward the realization of InGaN micro-substrates for efficient red emitting micro-LEDs

1. Growth

Arthur Sauvagnat[1]
Elias Semlali[1], Geoffrey Avit[1], Yamina André[1], Virginie Brändli[2], Benjamin Damilano[2], Vladimir. G Dubrovskii[3], Catherine Bougerol[4], Philip Shields[5], Névine Rochat[6], Eric Tournié[7], Thierry Taliercio[7], Agnès Trassoudaine[1]
[1] Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal, F-63000 Clermont-Ferrand, France
[2] Université Côte d'Azur, CNRS, CRHEA, rue Bernard Gregory, Sophia Antipolis, F-06560 Valbonne, France
[3] Faculty of Physics, St. Petersburg State University, St. Petersburg, Russia
[4] CNRS, Institut Néel, F-38042 Grenoble, France
[5] Department of Electronic & Electrical Engineering, University of Bath, England
[6] Univ. Grenoble Alpes, CEA, Leti, F-38000 Grenoble, France
[7] IES, UMR CNRS 5214, CC067, Université Montpellier 2, Place Eugène Bataillon, 34095 Montpellier Cedex 05, France

Abstract text: InGaN is a key material for high-performance optoelectronic devices due to its tunable bandgap from infrared to ultraviolet, depending on the indium content. However, growing high-indium content InGaN layers on GaN templates is challenging due to compressive strain, indium segregation, and thermal instability, which reduce the internal quantum efficiency, particularly for red emission. Nanowire (NW) architecture offers a solution by enabling strain relaxation and defect-free growth. InGaN NWs are also good candidates as seeds for micro-substrates, while hydride vapor phase epitaxy (HVPE) stands out for its high growth rates and composition control, making it a promising approach for InGaN micro-substrates fabrication [1,2].

This work demonstrates the selective area growth (SAG) by HVPE of well-ordered InGaN NWs with indium compositions spanning 0-100% on apertures varying from 200 to 500 nm. By using chlorinated precursors and optimizing III-element partial pressures ($InCl_3$, GaCl), we achieve homogeneous NW arrays. Optical properties, indium composition and crystalline quality were evaluated by photoluminescence and transmission electron microscopy experiments. A phenomenological growth model that considers III-element adsorption, along with diffusion, and chlorine-induced desorption offers deeper insight into the mechanisms of indium incorporation in the InGaN NWs. Further experiments are underway, including the growth of InGaN NWs in apertures as small as 40 nm. This approach would ensure the growth of a single NW per aperture, thereby enhancing the crystalline quality of the material. MOVPE regrowth of InGaN on relaxed HVPE-GaN nanopillars [3] is also planned, in an attempt to produce relaxed InGaN micro-substrates using this hybrid MOVPE/HVPE process. These findings and experiments should pave the way for InGaN micro-domains fabrication and their application for RGB nitride-based µLEDs.

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GR-Mon-P15* - Ultra-thick InGaN layers grown on sapphire substrate

1. Growth

Marketa Slavicka Zikova[1]
Tomas Hubacek[1], Jiri Pangrac[1], Frantisek Hajek[1], Karla Kuldova[1], Jiri Oswald[1], Pavel Hubik[1], Jan Batysta[2], Filip Dominec[1], Alice Hospodkova[1]
[1] FZU - Institute of Physics, Czech Academy of Sciences, Cukrovarnická 10, 16200, Prague 6, Czech Republic
[2] FZU - Institute of Physics, Czech Academy of Sciences, Cukrovarnická 10, 16200, Prague 6, Czech Republic; Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Bř

Abstract text: Nowadays, the production of green hydrogen is highly demanded due to the transformation of energy infrastructures around the world. Photoelectrochemical (PEC) or photocatalytic (PC) water splitting is a promising approach for zero-emission hydrogen production using solar energy [1]. InGaN nanowires have emerged as a promising structure for PEC or PC water splitting. InGaN has a great advantage in the tunability of the band gap to the water redox potential. It is also a very chemically stable material, making it suitable for water splitting applications. Mainly there have already been attempts, by so-called bottom-up approach, to grow InGaN nanowires by MBE [2]. However, there is a lack of knowledge about the growth of InGaN nanowires by MOVPE [3]. On the other hand, there is also the opposite approach, the top-down method, where thick InGaN layers can be grown and subsequently etched through a photolithography mask into microwire structures.

The preparation of MOVPE grown InGaN layers on GaN/substrate is well investigated. However, the thickness of such layers is limited by increasing strain due to different lattice parameters of InGaN and GaN. Therefore, after reaching a critical thickness, the InGaN layer relaxes, creating cracks and numerous defects.

To prevent this we grow InGaN layers by MOVPE directly on sapphire substrate. Different nucleation layers are investigated, and we show their influence on the structural and luminescence quality of thick InGaN layers (1 μm thickness). Next, we present the effects of various growth parameters, such as group-III precursor flow, showerhead gap, growth temperature, etc. The structural quality, surface morphology, transport and luminescence properties of the samples are evaluated and discussed with a respect to the growth conditions.

GR-Mon-P16* - 53 µm stress-free GaN grown on ceramics-AlN integrated substrates by MOCVD with simple AlN buffer

1. Growth

Junkang Wu[1]
Xuelin Yang[1], Zhenghao Chen[1], Hongcai Yang[1], Xingyu Fu[1], Faquan Wu[1], Yingming Song[1], Beile Chen[1], Lin Yao[1], Bo Shen[1]
[1] State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, Nano-optoelectronics Frontier Center of Ministry of Education, School of Physics, Peking University, Beijing 100871, P. R. China

Abstract text: Severe stress in GaN heteroepitaxial growth has long imposed limitaions on the film thickness and crystal quality, thereby affecting GaN device performance. This stress is attributed to the lattice mismatch and thermal mismatch between GaN and the heterogenous substrates. Ceramics-AlN, possessing compatible coefficient of thermal expansion (CTE) with GaN, is considered as a promising candidate to address this issue. With arbitrary dimensions and thickness, ceramics-AlN substrate also shows excellent compatibility, as well as high thermal conductivity and low cost. However, it is challenging to grow single crystal GaN directly on the ceramics-AlN substrate, due to the lack of single-crystal symmetry.

In this work, 53 µm stress-free GaN films were grown on ceramics-AlN integrated substrates by MOCVD with simple AlN buffer. First of all, ceramics-AlN integrated substrates were designed and fabricated, laying the fundation of fully stress-free GaN growth. Then, with a simple 50 nm MOCVD-AlN buffer, 3 µm, 10 µm and 53 µm GaN films were grown, showing completely crack-free surface. Moreover, all GaN samples were confirmed to be stress-free by Raman in-palne mapping and cross-section line scan. Finally, the 53 µm GaN sample exhibited a full width at the half maximum (FWHM) of 83 arcsec and 119 arcsec for the GaN(002) and GaN(102) rocking curve, respecitvely. A smooth atomic-steps surface with a root mean square (RMS) of 0.18 nm was observed on 53 µm GaN sample. The threading dislocation density (TDD) measured by cathodoluminescence (CL) of the 53 µm GaN sample were ~5e7 /cm2. To the best of our knowledge, the 53 µm GaN film is significantly thicker than that of other GaN films reported in the context of heteroepitaxial growth. This stress-free ultra-thick high-qulity GaN film paves a way for improving the performance of advanced GaN devices.

GR-Mon-P17 - Plasma-Assisted Molecular Beam Epitaxy of abrupt GaN/AlN/GaN-heterostructures on thin GaN-templates for High Electron Mobility Transistors

1. Growth

David Adolph[1]
Ingemar Persson[2], Tobias Tingberg[3], Tommy Ive[3], Mahdad Sadeghi[4], Peter Modh[4], Vanya Darachieva[5], Niklas Rorsman[1]
[1] Microwave Electronics Laboratory, Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, Göteborg, Sweden
[2] Department of Physics, Chemistry and Biology (IFM), Linköping University, Linköping, Sweden
[3] Former member of Photonics Laboratory, Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, Göteborg, Sweden
[4] Nanofabrication Laboratory, Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, Göteborg, Sweden
[5] Department of Physics, Chemistry and Biology (IFM), Linköping University, Linköping, Sweden (1) and Solid State Physics, NanoLund: Centre for Nanoscience, Lund University, Lund, Sweden (2)

Abstract text: MOCVD is the major growth method for high volume production of III-Nitrides. However there is a difficulty growing a 100% binary AlN-barrier HEMT without getting a ternary AlGaN-layer. With MBE it is possible to achieve an atomically abrupt transition between the GaN-buffer and the 100% binary AlN-barrier. O-levels should also be minimized in the growth process since AlN is sensitive for oxidation. MBE has a known problem of undesirable high O-impurities originating from the Ga in the effusion cells.

The aim of our work is to grow more complex heterostructures suitable for High Electron Mobility Transistors (HEMT:s) operating well beyond 100 GHz including re-grown contacts. To achieve this, we have successfully decontaminated an existing (As,P) EPI-930 MBE-system into a III-Nitride system. Our growth chamber shows a surprisingly record low Oxygen incorporation in MBE-grown GaN-layers at 1E16 atoms/cm^3 assessed with Secondary Ion Mass Spectroscopy (SIMS). For a GaN-cap(19nm)/AlN-barrrier(4.1nm)/GaN-channel (219 nm) on an MOCVD-grown QuanFINE®-template GaN(200 nm)/AlN(60 nm)/4H-SiC(0001) structure we have achieved a room-temperature Hall-mobility of 1640 cm^2/Vs, sheet resistance R_s=220 Ω/□, electron concentration n_s =1.73×10^{13} cm^{-2}. The XRC FWHM:s GaN(00.2) and GaN(20.1) are 142 and 495 arcsec respectively comparable to the substrate quality. The AFM peak to valley, and root mean square are 4.2 and 0.3 nm respectively.

In addition, we focus on the development of regrown contacts. We have achieved a sheet resistance R_s =12 Ω/□ with an electron concentration n=1.6 ×10^{20} cm^{-3} for a GaN:Si layer.

These results constitute the baseline for further processing of a full HEMT-structure. The achieved high mobility, low sheet resistance, low level of unintentional O-impurities and atomically abrupt GaN/AlN-interfaces for a 100% AlN-barrier are in all combination a promising foundation for further design and processing of a HEMT operating well above 100 GHz.

GR-Mon-P18 - A growth diagram of AlN epilayers grown by plasma-assisted molecular beam epitaxy

1. Growth

Pengfei Shao[1]
Yu Liu[1], Huan Liu[1], Tao Tao[1], Jin Wang[2], Junjun Xue[2], Zili Xie[1], Bin Liu[1], Dunjun Chen[1], Youdou Zheng[1], Rong Zhang[1], Ke Wang[1]
[1] Nanjing University, Nanjing, China
[2] Nanjing University of Posts and Telecommunications, Nanjing, China

Abstract text: A growth diagram of AlN epilayers grown by plasma-assisted molecular beam epitaxy

Pengfei Shao[1], Yu Liu[1], Huan Liu[1], Tao Tao[1], Jin Wang[2], Junjun Xue[2], Zili Xie[1], Bin Liu[1], Dunjun Chen[1], Youdou Zheng[1], Rong Zhang[1], Ke Wang[1,*]

[1] Nanjing University, Nanjing, China

[2] Nanjing University of Posts and Telecommunications, Nanjing, China

**E-mail: kewang@nju.edu.cn*

Ultrawide bandgap aluminum nitride (AlN) boasts high breakdown field strength, superior thermal conductivity, and exceptional stability, making it ideal semiconductor materials for high-power and high-temperature devices. However, due to the challenges in material growth, very limited work has been reported on AlN electronics.

In this work, we have investigated homoepitaxy of AlN films grown by molecular beam epitaxy (MBE) on AlN/sapphire templates. The MBE epitaxy of AlN at the low temperature range, which is suitable for AlGaN, encounters significant challenge in preventing Al droplet and pits, since the migration and desorption rate of Al atom are very low. In contrast, by elevating the growth temperature, such a difficulty can be effectively overcome, and we were able to grow AlN films with much improved surface morphology and obtained step flow growth mode without any Al droplets and pits. The cathodoluminescence spectroscopy indicate that the impurity incorporation and defect generation in the AlN epilayers was suppressed by elevating the growth temperature. A systematic investigation on the influence of Al beam flux and growth temperature in a very wide range on the AlN films has been conducted, and a comprehensive growth diagram of MBE AlN has been obtained.

GR-Mon-P19* - AlGaN buffer layers grown on sapphire substrates

1. Growth

Jan Batysta[1]
Alice Hospodková[1], Tomáš Hubáček[1], Jiří Pangrác[1], František Hájek[1], Karla Kuldová[1], Filip Dominec[1], Markéta Slavická Zíková[1], Michal Palič[1]
[1] Institute of Physics, Czech academy of sciences, Czechia

Abstract text: Growing AlGaN directly on sapphire has been identified as a niche area of research, since most applications involving AlGaN material can rely on a growth of binary compounds (GaN or AlN) as a nucleation and buffer layers. GaN has been identified as an optimal buffer layer for most of UVA emitters, however, with increasing Al content and layer thickness of AlGaN grown on top of GaN, the layers become susceptible to cracking due to a tensile strain. It is therefore technically relevant to manufacture light sources down to around 340 nm of emission wavelength. The employment of AlN as a buffer layer is beneficial for UVC and UVB range, and the utilization of AlN in UVB up to around 310 nm of emission wavelength was published [1]. This leads to a known gap with low external quantum efficiency (EQE) in the emission region 310-340 nm, as reported in [2].

In order to enhance EQE in the region of 340 to 310 nm, we propose the process of growing high quality AlGaN buffer directly on sapphire substrate. This process is generally considered as very difficult, due to the different Al and Ga adatom mobility causing phase separations and the emergence of defects [3]. This contribution will discuss a series of AlGaN buffers grown on sapphire using thin GaN nucleation, with concentration of Al of around 30%. Different growth process parameters will be discussed regarding the solid-state Al: Ga ratio, surface quality with regard to the “pancake defects” and threading dislocation density. These are evaluated via Raman spectroscopy, photoluminescence, scanning electron microscopy, etch pit density, and X-ray diffraction.

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GR-Mon-P20 - AlN/AlGaN/AlN Double Heterostructures: Towards AlGaN Channel High-Electron Mobility Transistors (HEMTs)

1. Growth

Hadi Sena[1]
Matti Lawton Siukola Thurston[2], Srabanti Chowdhury[1], **Nishita Sinha**[1]
[1] Department of Electrical Engineering, Stanford University, Stanford, California 94305, United States
[2] Department of Materials Science & Engineering, Stanford University, Stanford, California 94305, United States

Abstract text: Ultra-wide bandgap (UWBG) materials have garnered significant research and technological attention due to their potential for high-voltage power switching, high-frequency RF applications, and short-wavelength UV photonics, pushing the boundaries of electronics and photonics. This advancement is largely driven by emerging materials such as AlGaN, diamond, and Ga_2O_3, which have much wider bandgaps than conventional WBG semiconductors. Among these, AlGaN is particularly notable for its capability to create conductive channels through polarization-induced doping, making it a strong candidate for next-generation high-electron-mobility transistors (HEMTs).

In this study, we systematically examine the electronic properties of AlN/AlGaN/AlN heterostructures with varying AlGaN channel compositions, synthesized using metal-organic chemical vapor deposition (MOCVD). We also demonstrate that the thickness of both the channel and quantum barrier layers plays a crucial role in the formation of the 2DEG channel in AlGaN-based HEMTs.

AlN epilayers were deposited on c-plane sapphire substrates using a horizontal low-pressure MOCVD system. Growth conditions included a substrate temperature of 1450 °C for the AlN layer, with an AlN buffer grown at 1000 °C under a reactor pressure of 5 kPa. Following the deposition of an 800 nm AlN layer, AlGaN layers of different thicknesses were grown, followed by AlN barrier layers of varying thicknesses.

Electrical characterization included Hall-effect measurements using soldered indium corner contacts to the AlGaN channel 2DEG, along with capacitance–voltage profiling via a mercury probe to evaluate charge control in the heterostructure. Initial results indicated that the X-ray rocking curve of the AlN epilayer on sapphire exhibited a FWHM of 15 arcseconds. Optical and SEM imaging confirmed a smooth surface with no visible defects such as pits, cracks, or hillocks. C–V measurements at 1 MHz verified the presence of a 2D electron gas (2DEG) at the AlGaN/AlN interface, and Hall-effect measurements revealed a sheet carrier density of 2×10^{13} cm^{-2}, which closely aligned with our simulation results. Results showed that both 2DEG density and mobility increased as Al composition in AlGaN channel decreased. In addition, a strong dependence of 2DEG density and mobility on the channel thickness and barrier layer was confirmed.

GR-Mon-P21* - Analysis of the surface morphology of AlN and AlGaN grown on AlN bulk substrates with high off-cut angles up to 0.5°

1. Growth

Sarina Graupeter[1]
Sebastian Krüger[1], Massimo Grigoletto[2], Carsten Hartman[3], Thomas Straubinger[3], Tim Wernicke[1], Michael Kneissl[2]
[1] Technische Universität Berlin, Institute of Solid State Physics, Berlin, Germany
[2] Technische Universität Berlin, Institute of Solid State Physics, Berlin, Germany; Ferdinand-Braun-Institut, Berlin, Germany
[3] Leibniz-Institut für Kristallzüchtung, Berlin, Germany

Abstract text: The epitaxial growth of AlN and AlGaN on native AlN bulk substrates by metal organic vapor phase epitaxy (MOVPE) is crucial for advanced optoelectronic and electronic applications as the crystal quality and surface morphology of these layers has a strong impact on device performance. AlN bulk crystals offer a superior material quality with threading dislocation densities (TDDs) $<10^4$ cm^{-2} which need to be preserved during epitaxial growth of AlN and AlGaN layers. In addition, smooth surface morphology is required for AlGaN heterostructures which can be achieved through careful adjustment of growth parameters and AlN substrate off-cut. In this study, we investigate the influence of the AlN substrate off-cut angle (0.1° to 0.5°) as well as growth parameters (total gas flow, growth rate and V/III-ratio) on the morphology of AlN as well as AlGaN layers epitaxially grown on (0001) AlN bulk substrates.

AlN layers were grown by MOVPE using trimethylaluminum (TMAl) and ammonia as precursors. For the growth of AlN we find step flow morphology for an off-cut of 0.2°, a growth temperature of 1070°C, TMAl flow of 35 µmol/min and a V/III-ratio of 15. The morphology changes to step meandering for larger off-cut angles of 0.27° and step-bunching is observed for an off-cut of 0.39° and 0.5°. For an off-cut angle of 0.5° an increase of the V/III-ratio from 15 to 60 and total gas flow from 8 slm to 12 slm results in smooth step flow while preserving a growth rate of around 1.1µm/h. The density of threading dislocations in the epitaxial layer was determined using defect selective etching by Ba $(OH)_2$ melt. A etch pit density (EPD) of $1x10^6$ cm^{-2} was determined which is higher than the substrate's threading dislocation density but much lower than TDDs on sapphire. Subsequently, the growth of $Al_{0.76}Ga_{0.24}N$ on smooth AlN buffer layers was studied on AlN bulk substrates with off-cut angles between 0.2 and 0.5°. Since there are two adatom species present in AlGaN growth, the growth kinetics change and shift the regimes for step flow, step bunching and island growth to much higher V/III ratios. These results pave the way for the growth of full laser diode heterostructures on AlN bulk substrates with smooth surface morphologies and low defect densities.

GR-Mon-P22* - A New Method of Aluminiumization to Realize High-Quality of AlN Template on C-plane Sapphire

1. Growth

Amina Yasin[1]
Yuya Nagata[2], M. Ajmal Khan[1], Hideki Hirayama[1]
[1] RIKEN Cluster for Pioneering Research (CPR), 2-1 Hirosawa, Wako, Saitama, 351-0198 Japan
[2] Saitama University, Saitama 338-8570, Japan

Abstract text: Recently, 230nm far-ultraviolet-C (far-UVC) AlGaN-based light-emitting diodes (LEDs) have gained attention for their harmless effects on human skin and eyes while effectively disinfecting multidrug-resistant organisms, Candida auris and including SARS-CoV-2. However, their adoption is limited by low efficiency, mainly due to non-radiative recombination in the multi-quantum well (MQW) active region, caused by high threading dislocation density (TDD). A key source of dislocations is the AlN underlayer, where high TDD (~10^9 cm^{-2}) results from the large lattice mismatch between AlN and sapphire. Improving AlN underlayer quality is crucial for the mass production of low-cost AlGaN-based UV emitters. While single-crystal AlN substrates or thick AlGaN buffer layers improve material quality, these methods are costly and impractical for commercial-scale production. Instead, AlGaN materials grown on low-cost AlN templates on c-sapphire offer scalability, affordability, and UV transparency advantages. Our group previously optimized AlN template growth on c-sapphire using the NH_3 pulsed technique in MOCVD. However, further improvements in the crystal quality of AlN films grown on c-sapphire are necessary to capitalize on AlN template benefits for industrial applications. In this work, a new method, which we call it “Aluminiumization Technique” for the epitaxial growth of AlN was introduced. A thin aluminium metallic layer before the final AlN layer was introduced using MOCVD. During growth, trimethylaluminum was directly introduced without NH_3 flow, after nucleation. This method reduces excessive usage of NH_3, leading to reduced operational costs. We investigated the AlN crystal quality dependence on the thickness of the aluminiumized layer. We also investigated the AlN quality by varying the AlN buffer layer thickness. The full width at half maximum (FWHM) of the x-ray rocking curves in the improved AlN for the (0002) and (10–12) planes were reduced to 124 and 425 arcsec, respectively, indicating improved crystalline quality, when compared to conventional AlN template where the (0002) and (10–12) planes values were found to be 253 and 574 arcsec, respectively. The surface roughness also improved, with a root mean square (RMS) roughness of 0.08 nm, which is beneficial for the subsequent growth of far-UVC and UVB LED with higher internal-quantum efficiency.

GR-Mon-P23* - A novel approach to grow thick relaxed crack free Al0.5Ga0.5N on GaN for ultraviolet microdevices

1. Growth

Léa Lacomblez[1]
Philippe Vennéguès[1], Sébastien Chenot[1], Blandine Alloing[1], Benjamin Damilano[1], **Pierre-Marie Coulon**[1]
[1] Université Côte d'Azur, CNRS, CRHEA, Valbonne, France

Abstract text: The growth of UV transparent AlGaN material with low dislocation density (DD) and no cracks is mandatory to achieve efficient UV LED structures. AlGaN with low Al composition (up to 10-15%) can be grown on GaN template while higher Al composition (50-100%) are generally grown on AlN template. The limitation in Al composition and thickness of AlGaN layer grown on GaN arises from the generation of cracks, which occur due to lattice mismatch difference and thermal expansion coefficient difference. In addition, the flip chip layout being privileged in UV LEDs, it precludes the use of UV absorbing GaN template as well as the use of non-transparent silicon substrate. This explains why AlGaN LED heterostructures are essentially grown on AlN/sapphire template despite the ease to achieve GaN/sapphire template with DD in the low 10^8 cm^{-2}.

In this work, we present a novel approach to grow thick relaxed crack free AlGaN on GaN with Al composition up to 50%. First, a thin $Al_{0.15}Ga_{0.85}N$ pseudomorphic layer is grown on thick high quality GaN/sapphire template. Subsequently, micropillars are created via conventional optical lithography and chlorine-based dry etching. Thermal etching is then employed to gradually remove the GaN layer, resulting in $Al_{0.15}Ga_{0.85}N$ microdisks standing on a GaN pedestal. $Al_{0.5}Ga_{0.5}N$ regrowth is finally performed in order to create $Al_{0.5}Ga_{0.5}N$ micropallets. The morphology of the microstructures and of the *c*-plane surface has been monitored by scanning electron microscopy and atomic force microscopy. Structural quality and strain evolution of the various layers have been investigated by X-ray diffraction while cathodoluminescence has been used to assess the optical quality.

The key results are that, 1) the thin $Al_{0.15}Ga_{0.85}N$ microdisk successfully withstands the strain relaxation after GaN thermal etching, 2) the $Al_{0.15}Ga_{0.85}N$ microdisk acts as a compliant layer enabling the growth thick relaxed $Al_{0.5}Ga_{0.5}N$ micropallets, 3) $Al_{0.5}Ga_{0.5}N$ regrowth leads to the formation of micropallets with hexagonal shapes, flat surface, no cracks and no pits, 4) the DD is set by the one of the initial GaN template, in the order of 5.10^8 cm^{-2}. These findings together with the ease to transfer these micropallets on a host substrate, and therefore remove the absorbing GaN pedestal, hold many promises towards the fabrication of highly efficient UV microdevices.

GR-Mon-P24* - Controllable Step-Flow Growth of High-Quality Si-Doped AlN by Low-Temperature MOCVD

1. Growth

Huangshu Zhang[1]
Jiacheng Zhong[1], Jiahao Chen[1], Jiamin Chen[1], Zeren Wang[1], Zhijian Yang[1], Xuelin Yang[1], Lun Dai[1], Jiejun Wu[1], Tongjun Yu[1]
[1] School of Physics, Peking University, Beijing, China

Abstract text: Low-temperature doping offers a promising solution to the challenge of conductivity control in aluminum nitride (AlN)[1,2], a material with significant potential for next-generation optoelectronics and electronics[3]. Traditional metal-organic chemical vapor deposition (MOCVD) for high-quality AlN growth typically requires high temperatures. To overcome this, we have developed a method called "controllable step-flow growth," which makes full use of the limited diffusion capability of Al adatoms. We carefully design the stepped surface structures with varying terrace widths by supersaturation control. In a comparative study conducted at 1050°C, a long-lasting stable step-flow growth is achieved on the well-design surface, producing 3μm-thick Si-doped AlN with a conductivity of 56.1 $k\Omega^{-1}\cdot cm^{-1}$. Remarkably, the growth temperature is demonstrated to be further reduced to 980°C, a record low growth temperature of the AlN MOCVD process, and a conductivity of 115 $k\Omega^{-1}\cdot cm^{-1}$ is realized, which reaches the leading-level in the MOCVD-grown AlN. This approach not only expands the growth window but also provides critical insights into the surface kinetics of AlN epitaxy. By lowering thermal budgets and reducing equipment requirements, this method significantly cuts production costs, making it more feasible for industrial applications. Our findings demonstrate the potential of controllable step-flow growth to advance the use of AlN as a semiconductor, paving the way for its broader adoption in next-generation technologies.

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GR-Mon-P25* - Controlling Polarity of AlN/Si(111) over 200 mm by Magnetron Sputter Epitaxy Using a Double Ring Magnetron

1. Growth

Valentin Garbe[1]
Morris Ott[1], Agnė Žukauskaitė[2], Hagen Bartzsch[1], Elizabeth von Hauff[1]
[1] Fraunhofer Institute for Electron Beam and Plasma Technology FEP, D-01277 Dresden, Germany
[2] Institute of Solid State Electronics, Technische Universität Dresden, D-01069 Dresden, Germany

Abstract text: Advancing III-nitride epitaxy is key to low-cost energy-efficient power electronics, and a simplified polarity control of this wurtzite semiconductor family will unlock novel high-performance devices. Magnetron sputter epitaxy (MSE) is an emerging technology for III-nitride growth and has recently became a promising candidate for high-thruput, low-cost, and more environmentally friendly technology as an alternative to state-of-the-art Metal-Organic-Chemical-Vapor-Deposition (MOCVD).[1,2] Also, MSE enables reduced temperature process (<1000°C), simplyfying stress management and paving the way for improved material quality and device reliability, while potentially allowing monolithic integration with Si-CMOS process chain. On a laboratory scale, MSE deposition of device grade AlN and GaN semiconductor thin films for power electronics has been demonstrated.[3] To achieve high-volume MSE, high growth rates, low lattice damage, and homogeneous deposition on large-scale substrates are essential.

In this contribution we present our latest achievements of high-rate AlN MSE on a 200 mm Si(111) platform using a Double Ring Magnetron (DRM) technology developed by Fraunhofer FEP. The DRM enables a sputtering process in the transition region between metallic and reactive mode through unipolar and bipolar DC pulse mode operation, referred to as controlled reactive magnetron sputtering. This allows a process window with less kinetic energy bombardment of the substrate, resulting in improved film quality while maintaining high growth rates. In addition, we show for the first time that the polarity of the AlN epitaxial layer (Al- or N-polar) can be controlled just by the MSE process itself, which is not possible with MOCVD. Epitaxial Al- and N-polar AlN is deposited with growth rates >1 nm/s and at substrate temperatures below 800°C. An in-depth analysis of the grown AlN layers reveals that homogeneous film thickness (500±25 nm), crystalline quality (ω-FWHM 0.6° and 0.9° for the 00.2 and 10.1 reflection), topography (RMS 0.8±3 nm), polarity (Al- or N-polar), and residual film stress (1500 MPa and 800 MPa for Al-polar and N-polar) is achieved by precise process control.

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GR-Mon-P26 - Crystalline Quality Improvement of Low-Al Content AlGaN via Micropatterning and Coalescence

1. Growth

Vitaly Zubialevich[1]
Peter Milner[2], Sandeep Singh[2], Pietro Pampili[1], Peter Parbrook[2]
[1] Tyndall National Institute, University College Cork, Lee Maltings Dyke Parade, T12 R5CP Cork, Ireland
[2] Tyndall National Institute, University College Cork, Lee Maltings Dyke Parade, T12 R5CP Cork, Ireland; School of Engineering, University College Cork, Cork, Ireland

Abstract text: Low-to-medium Al-content AlGaN is a key material for UVA LEDs used in phototherapy and spectroscopy. Unfortunately, due to pinning by alloy fluctuations, dislocation annihilation in AlGaN is inhibited, leading to a poorer crystalline quality than for GaN or AlN. While high-to-medium and very-low Al-content AlGaN can be coherently grown on AlN and GaN templates, respectively, low-to-medium Al-content AlGaN suffers from cracking on GaN and plastic relaxation on AlN, preventing the inheritance of good crystalline quality from either substrate. This explains the lower efficiency of LEDs emitting around 330 nm compared to those around 280 nm [1] despite the stronger severity of other factors that make UV LEDs less efficient than their visible counterparts.

We propose overcoming this limitation by conventionally growing AlGaN via MOCVD on foreign substrates, patterning them at the nano/micro-scale to remove defective material, and regrowing higher-quality material while coalescing it back to planar layers. Our prior work focused on the morphological evolution of such overgrown micropatterned structures [2]. Here, we analyse the crystalline quality of fully coalesced AlGaN layers.

Initial ~2 µm-thick AlGaN templates were grown in a showerhead-type Aixtron MOCVD reactor on AlN/sapphire templates (Kyma Technology, Inc.) with a ~200 nm AlN connecting layer. X-ray diffraction indicates typical dislocation densities of low 10^7 cm^{-3} (screw-type) and ~10^{10} cm^{-3} (edge-type). A triangular array of 2 µm circular holes (3 µm pitch) was patterned via optical lithography and inductively coupled plasma dry etching. To remove etch-damaged material and further expand the holes, the samples underwent a wet KOH-based etch at 90°C, forming self-limited hexagonal holes with nearly *m*-plane sidewalls.

Coalescing these micro-honeycomb structures resulted in an almost order-of-magnitude reduction in the dominant edge-type dislocations at the cost of a several-fold increase in screw-type. The mechanisms behind this substantial crystalline quality improvement will be discussed in detail.

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GR-Mon-P27* - Epitaxial Strain Reconfiguration of AlGaN Multiple Heterojunctions for High-responsivity High-speed UV Detection

1. Growth
Zesheng Lv[1]
Zhuoya Peng[1], **Hao Jiang**[1]
[1] Sun Yat-sen University, Guangzhou, China

Abstract text: Achieving simple and efficient strain engineering remains a persistent challenge in AlGaN based material and device research, thereby substantially hampering the realization of the inherent material advantages. In this study, a strain reconfiguration strategy utilizing a medium-temperature AlN (MT-AlN) interlayer is proposed. By optimizing the MT-AlN thickness at 1000°C, tensile strain originating from the GaN template is systematically released through interfacial relaxation and lattice redistribution within the interlayer. Additionally, the engineered configuration also establishes a coherent crystalline template with programmable strain states for subsequent epitaxial growth.With a 25-nm optimized interlayer, crack-free $Al_{0.35\sim0}GaN$ multiple heterojunctions are epitaxially grown on the GaN template with slight compressive strain and nearly no additional dislocations (Figure 1). The resultant high-crystallinity AlGaN heterostructures enables the UV photodetector to achieve high responsivity (962 A/W) and record-fast response speed (0.6/25.4 ns rise/fall time) simultaneously, by introducing an electron-heating effect from the bandgap variations. All these collectively validate the MT-AlN strain reconfiguration as a viable pathway for the advancement of AlGaN-based optoelectronic devices.

GR-Mon-P28* - From UV-B to UV-C emission in core-shell structures based on (Al)GaN-micro-pillars arrays

1. Growth

Houssein MOHAIDLY[1]
Lucas JALOUSTRE[2], Saron-Rosy SALES DE MELLO[2], Lucie VALERA[1], Camille PETIT-ETIENNE[2], Erwine PARGON[2], Gwénolé JACOPIN[3], Christophe DURAND[1]
[1] Univ. Grenoble Alpes, CEA,Grenoble-INP, IRIG, PHELIQS, NPSC, 38000 Grenoble, France
[2] Univ. Grenoble Alpes, CNRS, CEA/LETI-Minatec, Grenoble INP, LTM, 38000 Grenoble, France
[3] Univ. Grenoble Alpes, Grenoble-INP, CNRS, Institut Néel, 38000 Grenoble, France

Abstract text: The development of UV micro-light-emitting diodes (µLEDs) is an emerging topic due to their potential applications such as UV µ-displays for RGB phosphor activation, flexible UV devices, in addition to high-speed solar-blind wireless optical communication.[1] Planar UV LEDs suffer from high defect densities, strain-induced cracking, and limited light extraction efficiency. To overcome these issues, we develop GaN/AlGaN core-shell multiple quantum wells (MQWs) grown by metal-organic vapor phase epitaxy,[2,3] based on GaN µ-pillar organized arrays obtained by top-down dry and wet etching process allowing access to a-, m-, and c-planes.[4,5]

In this study, we observe intense UV emission coming from a-planes in the range of 340-300 nm. We demonstrate that this emission can be tuned either with µpillar densities (S =15, 5, 2µm) or GaN well thickness by changing GaN growth time (65, 30, 15 s). Only a-planes are emitting, while emission intensity of m-planes is very weak, in addition to the presence of high density of horizontal cracks (about 2.1 μm^{-1}). However, the m-plane emission is highly enhanced using high V/III ratio, consistent with the limitation of point defect formation. Moreover, the introduction of an AlGaN shell spacer prior MQWs allow to mitigate cracking (crack density reduced to 1.3 μm^{-1}), while achieving a UV shift in emission wavelength to reach 280 nm region.

Building on these results, we are now advancing toward the UV-C regime by replacing the GaN with n-doped $Al_{0.6}Ga_{0.4}N$ pillar arrays. We develop $Al_{0.6}Ga_{0.4}N$/AlN core-shell MQW heterostructure, where we demonstrate far UV-C core-shell emission in the range of 240-220 nm without any crack formation. This approach opens the road to achieve the deep UV-C µ-LED based on a µ-wire arrays.

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GR-Mon-P29* - Hot-Wall MOCVD of AlN/Al0.80Ga0.20N/AlN HEMTs on AlN substrates: Growth and 2DEG Properties

1. Growth

Minho Kim[1]
Alexis Papamichail[2], Vallery Stanishev[3], Vanya Darakchieva[4]
[1] Wallenberg Initiative Materials Science for Sustainability (WISE), Department of Physics, Chemistry and Biology (IFM), Linköping University, SE-58183 Linköping, Sweden
[2] Center for III-Nitride Technology, C3NiT-Janzén, Linköping University, SE-58183 Linköping, Sweden
[3] Center for III-Nitride Technology, C3NiT-Janzén, NanoLund and Lund University, S-22100 Lund, Sweden
[4] Wallenberg Initiative Materials Science for Sustainability (WISE), Department of Physics, Chemistry and Biology (IFM), Linköping University, SE-58183 Linköping, Sweden;Center for III-Nitride Technology, C3NiT-Janzén, NanoLund and Lund University, S-22100 Lund, Sweden; Terahertz Materials Analysis Center, THeMAC, Lund University, S-22100 Lund, Sweden

Abstract text: High-Al-content AlGaN materials are promising ultra-wide bandgap semiconductors for power electronics, excelling in unipolar and lateral figures of merit and showing strong potential for high-frequency power transistors. Simulations suggest optimal performance at ~70%–90% Al due to the sharp thermal conductivity decline with increasing Al content, a critical limitation at high operating temperatures. Above 90% Al, insufficient polarization charge prevents 2DEG formation in AlN/AlGaN HEMTs, making 70%–90% the ideal range. However, research is limited by challenges in achieving low ohmic contact resistance. Recent advances in optical Hall effect (OHE) measurements provide a non-contact solution for characterizing bulk free charge carriers and 2DEG properties, addressing these limitations [1].

In this study, we develop homoepitaxial growth of AlN/$Al_{0.80}Ga_{0.20}N$ HEMTs on AlN substrates using hot-wall MOCVD to overcome strain and defect challenges associated with heteroepitaxy on SiC. Simultaneous growth on AlN and SiC allows for direct substrate comparison and growth behavior analysis by varying key parameters such as temperature, pressure, and V/III ratio. Our results show that AlN/$Al_{0.80}Ga_{0.20}N$ grown on AlN substrates exhibits a step-like morphology and superior structural quality compared to SiC, benefiting from the low-defect density and high thermal conductivity of native AlN. Furthermore, terahertz optical Hall effect measurements reveal higher 2DEG density for the structures grown on AlN substrates with respect to their SiC counterparts and confirm an optimized AlN/$Al_{0.80}Ga_{0.20}N$ heterostructure suitable for HEMT applications. At optimized growth conditions a 2DEG mobility of 404 $cm^2/(Vs)$, density of $4x10^{12}$ cm^{-2} and effective mass of $0.48m_o$ were obtained at 10K. This research provides valuable insights into high-Al-content AlGaN-based HEMTs and further strengthens their potential for electronic devices.

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GR-Mon-P30* - Implanted Si-Doping in Homoepitaxial AlN grown using Conventional and Pulsed MOCVD

1. Growth

Tariq Jamil[1]
Muhammad Ali[1], Abdullah Al Mamun Mazumder[1], Mafruda Rahman[1], Jingyu Lin[2], Hongxing Jiang[2], Grigory Simin[1], Asif Khan[1]
[1] Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208, USA
[2] Department of Electrical & Computer Engineering, Texas Tech University, TX 79409, USA

Abstract text: To exploit its high Baliga Figure of Merit, several groups are exploring doping control in Aluminum Nitride (AlN). Recently we reported pulsed metalorganic chemical vapor deposition (PMOCVD) Si-doping in homoepitaxial AlN with an efficiency higher than conventional MOCVD. We also found the highest conductivity films had the smallest sub-bandgap emission peak (at 3.2 eV) from the Al-vacancies due to Si-doping. Here we report a comparative study of Si-ion-implantation doping of homoepitaxial AlN films grown using conventional and pulsed MOCVD.

Conventional and PMOCVD (1150 ºC and 40 torr) grown 200 nm thick homoepitaxial AlN films were Si-ion-implanted at room temperature. The implant consisted of beam energies of 25 keV and 100 keV with a dose of $1x10^{14}$ atoms/cm^3. SIMS data confirmed a near uniform profile of approximately 2×10^{19} cm^{-3} silicon dopant atoms. A post implant 1150 ºC, 2-hour anneal under flowing nitrogen was used to remove the implant damage. The 0002 on-axis and the 1012 off axis X-ray peaks, recovered to their original positions and linewidths (off axis ~ 39 and 21 arc-sec and on-axis ~26 and 15 arc secs for the conventional and PMOCVD layers, respectively).

We fabricated Transmission Line Model (TLM) test structures with contact spacing from 2 to 20 µm on both samples using Zr/Al/Mo/Au (15/10/40/30 nm). They were annealed at 950 ºC for 30 sec. At 30 V bias, the currents for 2 µm spacing TLM pads for the conventional and the PMOCVD samples were 150 µA and 600 µA, respectively (factor of 4). High temperature TLM data for a 6 µm spacing were then used to extract the ionization energies of the two sample types as ~140 meV (conventional) and ~100 meV (PMOCVD). The room temperature photoluminescence (PL) the PMOCVD Si-implanted samples show a strong band-edge PL peak at 5.91 eV and no Al-vacancy Si complex peak (typically at 3.21 eV). On the contrary, the conventional MOCVD sample shows no band-edge luminescence and a small defect peak at 3.21 eV. The 2.5 eV peak (both samples) we confirmed is from the bulk AlN substrate. From these data we see that the overall quality of the PMOCVD sample is superior, and the implant/anneal process did not result in any compensating Al-vacancy-silicon complexes. Our data thus establishes Si-implantation in pulsed MOCVD AlN to be a potentially useful technique for selective area *n*-type doping.

GR-Mon-P31 - High Al-content Heterostructures Based on Dodecagonal AlGaN Microrods for Novel UV Emitter Applications

1. Growth

Paulina Ciechanowicz[1]
Łukasz Janicki[1], Robert Kudrawiec[1], Detlef Hommel[1]
[1] Łukasiewicz Research Network – PORT Polish Center for Technology Development

Abstract text: Arsenic-induced VLS-MBE growth has been proposed for the development of novel 12-sided GaN microrods with stable *a*- and *m*-planes [1]. These structures are a promising basis for novel UV emitters, offering an improved surface-to-volume ratio that can enhance light extraction. The three-dimensional VLS growth mode enables the formation of high-quality structures with a low defect density, minimizing strain-related issues observed in planar GaN layers. Such characteristics make them highly attractive for optoelectronic applications, where material quality and light extraction efficiency play a crucial role in device performance. Recent studies have shown that arsenic continues to act as an antisurfactant, promoting the growth of microrods over a broad temperature range. However, high-quality dodecagonal GaN microrods form optimally on GaN/sapphire substrates within a narrow window of 760-800°C [2].

The development of III-N microrods for UV emitters requires the incorporation of Al-containing heterostructures, which introduces challenges due to the different growth conditions needed for AlGaN compared to GaN. Specifically, the growth of AlGaN typically demands higher substrate temperatures to achieve optimal material quality. Additionally, for the successful fabrication of AlGaN microrods, it is essential to use an AlN substrate, which provides a better lattice match and minimizes strain-related defects.

This study focuses on the formation of AlGaN/AlGaN heterostructures within microrods, aimed at exploring their potential for UV emission. XRD and cathodoluminescence (CL) measurements were performed to analyze the composition and optical properties of these structures. The CL studies provide insights into the emission wavelengths of AlGaN/AlGaN layers, offering valuable data for understanding their optical characteristics in detail.

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GR-Mon-P32* - Low-temperature growth of Al monolayer on 7×7 reconstructed Si(111) surface by molecular beam epitaxy

1. Growth

Nhu Tran[1]
Philipp John[2], YongJin Cho[2], Roman Gröger[3]
[1] Institute of Physics of Materials, Czech Academy of Sciences, Žižkova 22, 616 00 Brno, Department of Condensed Matter Physics, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic
[2] Paul Drude Institute for Solid State Electronics, Hausvogteiplatz 5-7, 10117 Berlin, Germany
[3] Institute of Physics of Materials and CEITEC IPM, Czech Academy of Sciences, Žižkova 22, 616 00 Brno, Czech Republic

Abstract text: AlN serves as a nucleation layer for the growth of III-nitride materials on Si(111). The quality of these heterostructures is critically influenced by the initial film growth conditions, particularly the extent and morphology of Si surface coverage by Al. In this study, low-temperature molecular beam epitaxy (MBE) was employed to achieve uniform coverage of the 7×7 reconstructed Si(111) surface with Al. Surface structure evolution during Al deposition was monitored using reflection high-energy electron diffraction (RHEED). The low-temperature MBE process saturates Si dangling bonds with a single layer of Al atoms while preserving the original 7×7 reconstruction. X-ray photoelectron spectroscopy (XPS) confirmed the complete saturation of Si dangling bonds by Al adatoms. Atomic force microscopy (AFM) was used to characterize the surface roughness of air-exposed samples and evaluate the density of undesired Al nanoclusters. These films will serve as a platform for subsequent layer-by-layer MBE deposition of AlN at low temperatures, followed by metal-organic chemical vapour deposition (MOCVD) to grow thicker films.

GR-Mon-P33 - Molecular beam epitaxy of GaN/AlxGa1-xN quantum wells on high-quality GaN substrates for indirect exciton diffusion

1. Growth

Benjamin Damilano[1]
Rémi Aristégui[2], Henryk Teisseyre[3], Vincent Guigoz[1], Aimeric Courville[1], Ileana Florea[1], Denis Lefebvre[1], Philippe Vennéguès[1], Michal Bockowski[4], Thierry Guillet[2], Masha Vladimirova[2]
[1] Université Côte d'Azur, CNRS, CRHEA, Valbonne, France
[2] L2C, University of Montpellier, CNRS, Montpellier, France
[3] Institute of Physics, Polish Academy of Sciences, Warsaw, Poland
[4] Institute of High-Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: In wide polar III-nitride quantum wells, there is a notable separation between the exciton and hole wavefunctions, which results in the formation of what is referred to as an indirect exciton. This spatial separation enhances the dipolar interactions between indirect excitons, leading to significant correlations among them, the emergence of collective phenomena, and the potential for transitions into new many-body quantum phases. One critical characteristic of these wide quantum wells is their extended radiative lifetime for excitons, which can exceed 1 µs. In contrast, narrow quantum wells typically exhibit much shorter lifetimes on the order of 1 ns. Consequently, it becomes essential to utilize high-quality substrates to mitigate the effects of non-radiative recombinations that can occur due to a high density of threading dislocations present in the material.

For our experiments, we have grown GaN / $Al_xGa_{1-x}N$ quantum wells with a low aluminum content (less than 0.1) and quantum well widths ranging from 5 to 10 nm. These structures were fabricated using ammonia-based molecular beam epitaxy on high-quality GaN substrates. The threading dislocation densities of these substrates are in a range of approximately 10^4 cm^{-2} or 10^6 cm^{-2}. The high quality of these substrates is critical for ensuring a large internal quantum efficiency and enabling a significant exciton diffusion length.

The advantage of using such high-quality substrates is that they allow us to explore the growth modes of GaN/$Al_xGa_{1-x}N$ without the disruptive effects typically associated with the presence of dislocations, such as strain fields and spiral growth patterns. Our investigations reveal that the growth mode can be systematically tuned by varying the V/III ratio, growth temperature, and the substrate's offcut angle. Through optimization of these growth conditions, we achieved a low root mean square surface roughness of 0.18 nm as measured using atomic force microscopy over a scanning area of 50x50 µm². Low-temperature photoluminescence measurements showed a narrow linewidth of 5.7 meV for a quantum well with an aluminum composition of 0.1. Additionally, we demonstrated the ability of indirect excitons to diffuse across distances greater than 150 µm.

GR-Mon-P34* - Reactive High-Temperature-Annealing of Aluminum Nitride on Sapphire in Ammonia and Carbon Monoxide

1. Growth

Karl Kreuzer[1]
Christoph Margenfeld[1], Lukas Abel[1], Lukas Peters[1], Jana Hartmann[1], Andreas Waag[1]
[1] Nitride Technology Center, Institute of Semiconductor Technology, Technische Universität Braunschweig, 38106 Braunschweig, Germany

Abstract text: High-temperature-annealing (HTA) of aluminum nitride (AlN) on sapphire enables AlN templates with very low threading dislocation densities (TDDs) of ~ $5 \cdot 10^8$ cm^{-2}.[1] Typically, a 300 nm thin AlN layer is sputter-deposited on sapphire and subsequently annealed at around 1700°C.[1] The high temperatures during annealing lead to oxygen out-diffusion from the sapphire substrate and hence to an increasing oxygen concentration in the AlN layer.[2] Besides the incorporation of oxygen into the AlN film, aluminum oxynitride (AlON) patches are formed on the surface of the AlN layer.[3] Those AlON patches cause large hexagonal hillocks during AlN regrowth.[4] For high-quality regrowth, its important to either avoid the formation of AlON patches during HTA, or remove these patches after HTA. Both approaches can be addressed by reactive HTA under either ammonia or carbon monoxide atmosphere, which is the topic of this work.

First, we have investigated in-situ ammonia-cleaning of the templates directly after HTA in the HT furnace. After cleaning, we observe a drastic reduction of the RMS roughness accompanied by a clearly visible smoothening of the surface. Similar surface morphologies can be achieved by an ammonia-bake in a MOVPE reactor. Our results indicate that a high-temperature ammonia treatment after HTA can remove AlON.

In a second experiment, carbon monoxide-nitrogen atmospheres are used during HTA. A variation of the CO/N_2 ratio shifts the chemical equilibrium of the carbothermal nitridation reaction (CNR) $Al_2O_3 + 3C + N_2 \Leftrightarrow 2AlN + 3CO$ towards the AlN or sapphire side. With this approach, we can access the balanced regime of the carbothermal nitridation, where the total reaction velocity between AlN and Al_2O_3 vanishes. We observe a soft smoothening of the surface and a drastic transformation of AlON related defects when the CO/N_2 ratio is increased. Our results show that the formation of AlON can be adjusted by adding CO to the atmosphere. This demonstrates that HTA under reactive gas atmospheres is an interesting approach for increasing control over AlON formation during HTA, which is believed to be a prerequisite for obtaining high-quality AlN templates.

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GR-Mon-P35 - Revolutionary Performance of a High-Speed Vertical Rotating Disc Reactor for Aluminum-Containing Epitaxial Growth on (111) Silicon

1. Growth

Soo Min Lee[1]
Randhir Bubber[1], Ming Pan[1], Michael Coco[1], Bojan Mitrovic[1], Drew Hanser[1]
[1] Veeco Instruments Inc, Somerset, NJ, USA

Abstract text: Gas-phase parasitic reactions can influence the growth rates and quality of aluminum-containing epitaxial layers grown in a vertical rotating disc reactor when using TMAl and NH_3 as reactants. Increased disc rotation speeds result in higher AlN growth rates, which can be attributed to the fact that most of the irreversible decomposition of TMAl:NH_3 (amide formation) and oligomerization occur within the hot boundary layer, where residence time is strongly dependent on rotation speed [1]. In other words, high RPM conditions can enhance source consumption efficiency and even expand the process window for improving crystal quality during the growth of high aluminum-content layers.

In this study, MOCVD AlN films were grown on 300mm (111) Si substrates using a Veeco PROPEL® 300 single-wafer vertical disc rotating reactor, where the maximum disc rotation speed was increased from 1200 rpm to 2500 rpm. The effects of varying disc rotation speed, V/III ratio, growth pressure, growth temperature, and N_2/H_2 gas ambient on AlN surface morphology, growth rate, crystal quality (AlN(002), AlN(102) rocking curve), and vertical leakage current were investigated. At a chamber pressure of 35 Torr, a growth temperature of 1036°C, and an H_2 ambient, increasing the disc rotation rate from 1200 rpm to 2500 rpm resulted in a 1.7× increase in growth rate at a V/III ratio of 452, and a 2.4× increase at a V/III ratio of 150. The high RPM capability successfully improved AlN quality. When AlN growth was optimized at 2500 rpm and 1100°C, crystal quality improved from (002)w ~ 1100 arcsec to 950 arcsec, and pit density on the AlN layer was dramatically reduced due to the shift to a two-dimensional growth mode.

These observations support the expected improvements in growth efficiency and material quality, which are consistent with the theory of reduced gas-phase reactions at high-speed wafer rotation.

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GR-Mon-P36 - The Impact of Mg doping on the hopping conduction of p-type Al-rich AlGaN

1. Growth

Zhibin Liu[1]
Rui Ren[1], Yanan Guo[1], Jianchang Yan[1], Junxi Wang[1]
[1] Research and Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

Abstract text: The poor conductivity of the p-type Al-rich AlGaN layer is one of the primary challenges for the improvement of AlGaN-based lighting emitters. The solubility of the dopant magnesium decreases with increasing the Al content [1]. The ionization energy of Mg in AlGaN increases from 180 meV to 610 meV. In addition, the self-compensation effect caused by donor-type defects further exacerbates the issue [2].

This work investigates the impact of Mg doping on the Hall characteristic of $Al_{0.6}Ga_{0.4}N$. The p-AlGaN layer was grown by metal organic chemical vapor deposition with a growth pressure of 100 mbar and a growth temperature of 1010 °C. The flow rates of TMAl, TMGa and NH_3 were 69 sccm, 13 sccm, 12000 sccm, respectively. The Cp2Mg flow rate was varied at 700 sccm, 1000 sccm, and 1800 sccm.

According to the temperature-dependent Hall measurement results, all samples have a negative Hall coefficient which means that hopping conduction is dominant at low temperatures (<500 K). The fitting results shows the activation energy for hopping conduction is 56 meV, which is much smaller than the theoretical activity energy of Mg in p-$Al_{0.6}Ga_{0.4}N$. As the temperature increases (>500 K), a part of Mg dopants is ionized and the conduction mechanism starts to transit towards valence band conduction. However, the Hall coefficient remains negative, suggesting that the hopping conduction still plays a significant role. When the Mg flow rate increases from 700 sccm to 1000 sccm, the conductivity significantly increases. When the Mg flow rate further increases to 1800 sccm, nitrogen vacancy defects and defects associated with polarity inversion domains significantly increase. These defects cause a self-compensation effect, leading to a noticeable decrease in the conductivity of p-AlGaN. This is consistent with the increase of the oxygen impurity in p-AlGaN with the Mg flow rate of 1800 sccm. Finally, the high-conductivity p-type $Al_{0.6}Ga_{0.4}N$ (0.12 S/cm at room temperature) is achieved with the Mg flow rate of 1000 sccm. This work provides important guidance for the growth of p-type Al-rich AlGaN layers with high conductivity. The details will be discussed on the conference.

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GR-Mon-P37 - Vertically Conductive AlGaN Epilayers for Next Generation Power Electronics and UV Light Emitters

1. Growth

Pawel Prystawko[1]
Marcin Krysko[1], Jerzy Plesiewicz[1], Rafal Bozek[2], Michal Swiatek[2], Ewa Grzanka[1], Fabrizio Raccaforte[3], Andrzej Wysmolek[2]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland
[2] Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland
[3] CNR-IMM, Strada VIII, 5, 95121 Catania, Italy

Abstract text: AlGaN epilayers are widely used in high electron mobility transistors as well as ultraviolet LEDs and photodetectors, mostly on SiC Si and sometimes on native GaN and AlN substrates. However, next generation Power Electronics and deep UV emitters require thick layers with significant concentration of aluminium and cannot be strained to GaN nor AlN[1]. In addition, those future devices' performance and reliability relies on true vertical current flow, what is not possible using insulating substrates.

In this study, a range of silicon doped $Al_xGa_{1-x}N$ (x from 0.08 to 0.8) epilayers were grown using metal-organic chemical vapor deposition (MOCVD) on various conductive substrates like n-type ammonothermal GaN (Am-GaN) [2], n-type on-axis 4H-SiC as well as h-BN on sapphire [3] aiming complete relaxation and preserving vertical conductive path. In this work, we examine the process of Van der Waals (VdW) epitaxy of AlGaN where nitride epilayers grown on h-BN/sapphire were lightly bonded thus spontanously delaminate after growth due to thermal strain and mismatch in coefficients of thermal expanssion (CTE). Using Am-GaN we performed both: pseudomorphic growth limitting the composition and thickness' of fully strained AlGaN as well as sacrificial intermediate layers to assist in relaxation of ternary compounds in order to check for the lower density limits of extended defect formation. On 4H-SiC we examined growth of low temperature AlN (LT-AlN) and replaced it with similar aided highy n-type ternary nucleation layer [4] followed by main AlGaN:Si. High resolution X-ray diffraction HR-XRD yelded the strain state and lattice parameters of test structures as well as determined composition of ternary epilayers. Optical and electrical characterization was performed on virgin material and vertical Ohmic and Ni/Au Schottky barier diodes (SBD), respectively. Atomic force microscopy (AFM) was used to evaluate surface roughness, and threading dislocation density (TDD).

This work was partially supported by *VISTOLA* bilateral agreement between CNR-IMM and IHPP-PAS.

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GR-Mon-P38* - Numerical and experimental analysis of ammonothermal crystal growth configurations and their impact on the temperature field along the autoclave wall

1. Growth

Thomas Wostatek[1]
Markus Zenk[2], Jochen Friedrich[2], Saskia Schimmel[1]
[1] Friedrich-Alexander-Universität Erlangen-Nürnberg, Chair of Electron Devices (LEB), 91058 Erlangen, Germany
[2] Fraunhofer Institute for Integrated Systems and Device Technology IISB, 91058 Erlangen, Germany

Abstract text: GaN devices manufactured on high-quality GaN substrate materials can open the door to new markets [1]. Amongst all existing bulk GaN growth techniques, the ammonothermal method delivers the highest structural quality [2]. Accordingly, GaN-on-ammonothermal GaN diodes demonstrate an outstanding breakdown voltage to on-resistance performance in benchmark tests [3]. So far, ammonothermal GaN has not yet reached the mass market and many questions on the process understanding are still pending [2].

Schimmel et al. showed that the temperature distribution and fluid flow inside the ammonothermal reactor (autoclave) are very sensitive to the temperature distribution along the autoclave wall [4]. The temperature distribution along the autoclave wall depends strongly on the actual ammonothermal configuration. A common configuration is a cylindrical autoclave in a multi-zone furnace, which in turn is placed in a type of an enclosure [5]. These components and their combination vary noticeably in the literature.

In this contribution, a comparison of different ammonothermal configurations will be given. Different autoclave materials (alloy 718, 282, 41 and TZM) and enclosure types (sealed with low N_2 exchange rate, not sealed with high air exchange rate) will be compared. Beyond that, the effect of different configurations of a heat sink in the baffle region (between the growth and dissolution region) will be studied. Numerical simulations of the thermal field using the multi-physics software CrysMAS (developed by Fraunhofer IISB) have been carried out for the different configurations. In addition, experiments were conducted for verification and validation. The simulated heater powers are in reasonable agreement with the experiments. The heat losses depend strongly on the gas exchange rates. Major heat losses occur at the head assembly and the heat sink in the baffle region. These have a strong effect on the temperature distribution along the autoclave wall.

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PC-Mon-P1 - Optical losses in epitaxial AlN on sapphire: the role of defects and the promising solution of a sputtered buffer layer for integrated photonics

2. Physics and characterization

Samuele Brunetta[1]
Samantha Sbarra[2], Brandon Shuen Yi Loke[2], Jean-François Carlin[1], Nicolas Grandjean[1], Camille-Sophie Brès[2], Raphaël Butté[1]
[1] Laboratory of Advanced Semiconductors for Photonics and Electronics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[2] Photonic Systems Laboratory, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Abstract text: Over the past decade, aluminum nitride (AlN) has gained increasing attention as an appealing material for both linear and nonlinear integrated photonics owing to its low optical losses over a broad transparency window—from the ultra-violet to the mid-infrared—, its high thermal conductivity, its relatively small thermo-optic coefficient and the presence of both second-and third-order intrinsic nonlinearities. More recently, single-crystalline AlN layers grown on sapphire by metalorganic vapor-phase epitaxy (MOVPE) have been preferred to sputter-deposited layers for photonic applications mainly due their lower optical losses. However, the material parameters responsible for optical losses have not been extensively studied, limiting potential advancements offered by this platform.

In this work, we present a systematic comparison of three types of AlN epilayers with a thickness above 1 µm, grown on *c*-plane sapphire: a fully MOVPE-grown layer (full-MOVPE), a layer grown by MOVPE on a thin sputtered AlN seed layer (hybrid), and a commercially available AlN epilayer.

For comparative purposes, waveguides and microring resonators were fabricated on the three epilayers by means of electron-beam lithography, dry etching and SiO_2 cladding deposition, and tested at 1550 nm. While for the full-MOVPE layer propagation losses in waveguides are as high as 33 dB/cm, we extracted intrinsic quality factors up to 1.6 million in microring resonators fabricated on both the hybrid and the commercially-available epilayers, corresponding to propagation losses of 0.24 dB/cm, a value comparable to previous results from the literature.

This remarkable difference in the optical performance can be explained by the presence of vertically elongated voids in the full-MOVPE layer that were detected by multiple methods including cross-section scanning electron microscopy, atomic force microscopy after partial layer thinning, and secondary-ion mass spectrometry impurity profiles. Such voids act as a source of volumetric scattering, as supported by 3D finite-difference time-domain simulations. Our results highlight the detrimental effect of voids in light propagation and indicate that hybrid layers are a powerful solution to obtain void-free, low-loss AlN epilayers with customizable thickness to target a wider range of integrated photonic applications.

PC-Mon-P2* - Multichannel Thermal Quenching of Si-Bound Excitons in AlN: Symmetry-Governed Exciton Transfer and Radiative Auger Process Competition

2. Physics and characterization

Guoping Li[1]
Ning Tang[1], Chen Ji[1], Qikun Wang[2], Liang Wu[2], Lei Fu[1], Shixiong Zhang[3], Shuaiyu Chen[1], Erfei Zhang[1], Tianyu Zhang[1], Fujun Xu[1], Weikun Ge[1], Bo Shen[1]
[1] State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China.
[2] Ultratrend Technologies Co., Ltd., Room 518, Building 3, No. 503, Shunfeng Road, Liping District, Hangzhou City, Zhejiang Province 311199, China.
[3] College of Physics and Electronic Science, Hubei Key Laboratory of Photoelectric Materials and Devices, Hubei Engineering Research Center for Micro-Nano Optoelectronic Devices and Intergration, Hubei

Abstract text: Aluminum nitride (AlN) offers a promising opportunity for the development of next-generation power electronics and deep ultraviolet optoelectronic devices due to its unique properties. In recent decades, silicon (Si) has been the most commonly used n-type dopant in AlN. However, achieving high-performance n-type conductivity in Si-doped AlN remains challenging due to compensation effects and DX center formation. The properties of Si in AlN can be studied using spectral techniques. Despite advancements, the origin of the thermal quenching of the neutral silicon-bound exciton (Si^0X) emission peak remains debated, and detailed studies on the recombination dynamics of Si^0X are still lacking.

In this work, for the first time, the thermal quenching mechanism and recombination dynamics of Si^0X emission peak in AlN are thoroughly investigated using steady-state photoluminescence (PL) and time-resolved photoluminescence (TRPL) spectroscopy. The multichannel thermal quenching of Si^0X emission peak in AlN is revealed, which is attributed to thermally activated processes from Si^0X to two free exciton states (Γ_1 and Γ_5), alongside the competing two-electron satellite (TES) transition. Among these, the activation process to the higher-energy Γ_1 free exciton state dominates, indicating that the rate of exciton transfer is symmetry-governed. The TES transition, regarded as a radiative Auger process, is evaluated for the first time regarding its role in the thermal quenching of Si^0X emission. At 4.5 K, TRPL measurements reveal the longest PL lifetime of Si^0X emission peak observed to date, reaching 160 ps. However, as temperature increases, the nonradiative recombination lifetime rapidly decreases, causing the PL lifetime to drop to 15 ps at 80 K. Meanwhile, the radiative recombination lifetime increases with temperature, further accelerating the thermal quenching of Si^0X emission. A widely applicable method for extracting the TES transition rate of donor-bound excitons in semiconductors is developed. Consequently, the observed non-monotonic temperature dependence of TES emission intensity is explained, which arises from the predominance of the thermally activated TES transition rate at low temperatures, as opposed to the delocalization tendency of Si^0X. This work provides a foundation for deeper insights into the properties of Si^0X and Si donor in AlN.

PC-Mon-P3* - Correlative analysis of threading dislocations in aluminium nitride layers

2. Physics and characterization

Marek Patočka[1]
Nikhilendu Tiwary[1], Sami Suihkonen[2], Mervi Paulasto-Kröckel[1]
[1] Aalto University, School of Electrical Engineering, 02150 Espoo, Finland
[2] VTT Technical Research Centre, 02044 Espoo, Finland

Abstract text: Threading dislocations (including edge, screw, and mixed dislocations) are among the most prevalent crystal defects in III-N semiconductors, significantly influencing their electrical properties. Traditionally, wet etching has been the method of choice for analysing threading dislocation density (TDD) [1]. However, due to the destructive nature of etching, alternative non-destructive methods and a combination of those such as electron channelling contrast imaging (ECCI), cathodoluminescence, estimates based on full-width half maximum of the rocking curve X-ray diffraction, or atomic force microscopy (AFM), have recently become more prevalent [2, 3]. Another advantage of these techniques is that they do not differentiate between metal-polar and nitrogen-polar AlN, whereas nitrogen-polar AlN cannot be analysed using etching-based methods because it gets etched away very quickly. Different analytical techniques are suitable for varying dislocation densities. For instance, films with high TDD are problematic for ECCI analysis because the dislocations overlap in the images, making them indistinguishable.

We present a study of TDD of multiple samples with particular emphasis on AlN grown on SiC substrates. In our work, we utilise multiple techniques to probe the TDD of aluminium nitride deposited by metalorganic chemical vapour deposition. Our case study focuses on finding accurate methods for interpreting the acquired data by correlating results from different techniques. The techniques utilised include the X-ray diffraction rocking curve measurement, AFM, and various electron microscopy techniques.

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PC-Mon-P4* - First observation of an optical signature for zinc-blende stacking faults in hexagonal AlN

2. Physics and characterization

Corentin Guérin[1]
Fabien Jourdan[2], Jean-Luc Rouvière[3], Bruno Gayral[2], Gwénolé Jacopin[4], Bruno Daudin[2]
[1] Univ. Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, NPSC / Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel
[2] Univ. Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, NPSC
[3] Univ. Grenoble Alpes, Grenoble INP, CEA, IRIG, MEM, LEMMA
[4] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel

Abstract text: Since the beginning of the race to replace UV-emitting mercury-lamps, Al(Ga)N has been highlighted for the realization of solid states UV-B and UV-C emitters (from 280nm to 220nm). Extensive growth/structural/optical studies were undertaken to reach an acceptable material quality for realization of such emitters. In our way to improve optical quality of AlN near band edge emission, we observed, for the first time, an unexpected optical emission around 5.85eV at 5K that we correlated to the presence of Basal Stacking Faults (BSF) in AlN. In fact, such BSFs have been intensively characterized in GaN in the literature [1], [2]. Moreover, it has been shown that their presence induced specific emission peaks depending on their thickness. But until now, no optical signature of these type of defects were observed in AlN. Indeed, it has been established that the formation energy of I1 BSF (one ABC inclusion in a ABAB matrix) in AlN is five times higher than in GaN, making their observation scarce in the literature [3]. In the case of nanowires we discovered that a specific growth mode i.e. Migration Enhanced Epitaxy (MEE) enhances the formation of I1 BSFs in AlN. The properties of these BSFs were characterized by TEM and cathodoluminescence. We first show that the peak emission consists of many contributions, around an average energy of 5.85eV. The averaging of these peaks by scanning a large number of nanowires with CL spot allows us to track an average behaviour as a function of temperature. We identified a trend to carrier localization at low temperature, suggesting the possible coupling of BSFs with donor/acceptor in their vicinity. This coupling have been already predicted by Cordfir et al. [2] for GaN BSF.

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PC-Mon-P5* - Time-resolved cathodoluminescence spectroscopy of oxygen-related defects in AlN layers

2. Physics and characterization

Barbara Szafranski[1]
Lukas Peters[1], Christoph Margenfeld[1], Stefan Wolter[1], Andreas Waag[1], Tobias Voss[1]
[1] Institute of Semiconductor Technology and Laboratory for Emerging Nanometrology, Technische Universität Braunschweig, Braunschweig, Germany

Abstract text: For the fabrication of AlGaN-based LEDs in the UV range, a high-quality AlN buffer layer on a sapphire substrate is presently viewed as a prerequisite for a high quantum efficiency. High temperature annealing (HTA) of sputtered AlN-on-sapphire substrates has been shown to substantially improve the crystal quality of the template. However, during the annealing process, oxygen diffusion from the sapphire substrate introduces a large density of point defects. These oxygen-related defects are considered to be responsible for the absorption in the deep UV below ~230 nm. [1] Simultaneously, the high oxygen doping concentration leads to n-type material, which explains the absence of the commonly observed absorption band for wavelengths around 265 nm. [2] To effectively optimize UV LED performance, a detailed understanding of the defect states introduced by oxygen during HTA and their impact on the template's optical properties is essential.

Therefore, we analyzed the influence of oxygen defects in HTA AlN layers using cathodoluminescence (CL) spectroscopy. The 350 nm thick AlN layers were treated with HTA at different temperatures. The process was optimized to lead to very high crystal quality.

At room temperature, CL spectroscopy shows a broad (FWHM of 466 meV) luminescence band centered at about 3.65 eV. We investigated the charge carrier dynamics of these oxygen-related defects in AlN using time-resolved cathodoluminescence spectroscopy. Characterization of the defect luminescence reveals a complex multi-exponential decay, with a fast component of about 2 ns and slow components of tens to hundreds of ns. The slow decay is attributed to a donor-acceptor-pair transition between an O_N donor and mainly the $(V_{Al}\text{-}O_N)^{2-}$ and $(V_{Al}\text{-}2O_N)^{1-}$ defect complexes as acceptors, whereas the fast component is ascribed to a free electron to acceptor transition involving the same type of acceptors. Consequences for applications as buffer layers for UVC LEDs will be discussed.

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PC-Mon-P6* - Investigation of dislocation types and line vectors of threading dislocations in aluminum nitride using monochromatic and white-beam X-ray topography

2. Physics and characterization

Leon Schiller[1]
Roland Weingärtner[1], Merve Kabukcuoglu[2], Gleb Lukin[1], Sven Besendörfer[1]
[1] Fraunhofer Institute for Integrated Systems and Device Technology, Erlangen, Germany
[2] Institute for Photon Science and Synchrotron Radiation, Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract text: Aluminum nitride (AlN) is a wide-bandgap semiconductor with potential applications in high-power electronics and optoelectronic devices. Wafer processing and device manufacturing require an ideally defect-free material and a large crystal diameter. Knowledge about the dislocation content is crucial for an improvement of the bulk crystal growth process regarding diameter enlargement as well as for the understanding of epitaxial layer quality and anomalous behavior of electronic devices. To date, there is no established technique that allows for obtaining such information on full wafer scale using laboratory equipment. A dislocation is characterized by its line vector and Burgers vector, which contain information about the orientation, type and strength of the dislocation. Due to the stress field around the dislocations, they appear as a local contrast in the measured topographic images depending on the diffraction conditions and can thus be visualized in spatial resolution.

In this work we investigate dislocation types and line vectors of threading dislocations (TDs) in AlN crystals and wafers, using monochromatic laboratory X-ray topography (XRT) and white-beam synchrotron XRT. The goal is to obtain reliable information about the full dislocation content in AlN samples to provide feedback for crystal growth. Comparison of the results obtained by monochromatic XRT with those performed by white-beam XRT allows us to develop an understanding of the capabilities and limitations of each setup. By using a geometric model for the interpretation of dislocations' contrasts on the detector and utilizing visibility criteria we show a full characterization of dislocations' line and Burgers vectors by combining measurements of different reflexes and orientations. By providing this analysis we can give a comprehensive overview about the different TDs that are present in a wafer. This information can be used to investigate the propagation of dislocations during multi-generation crystal growth and to correlate local electrical properties of epitaxial layers to different types of dislocations in the substrate. This represents an important step in the characterization of AlN and helps bringing the material closer to industrial applicability.

PC-Mon-P7* - Defect analysis comparing polarized stress imaging and X-ray topography methods on gallium nitride epitaxial layers on silicon and sapphire

2. Physics and characterization

Leon Schiller[1]
Teodóra Nagyné Kovács[2], Zsolt O. Kovács[2], Zsolt Kovács[2], Roland Weingärtner[1], Sven Besendörfer[1]
[1] Fraunhofer Institute for Integrated Systems and Device Technology IISB, Erlangen, Germany
[2] Semilab Semiconductor Physics Laboratory Co. Ltd., Budapest, Hungary

Abstract text: Gallium nitride (GaN) is a wide bandgap semiconductor for power electronics and high frequency applications. Today, the most industrially relevant types of GaN devices are high electron mobility transistors (HEMTs) fabricated on foreign substrates such as (111)-oriented silicon (Si), silicon carbide or sapphire. Lattice and thermal mismatch between the substrate and the epitaxial layers induce stress in both the substrate and the GaN layer, resulting in wafer bowing and formation of macroscopic defects and dislocations. The visualization of stress fields and macroscopic defects on full wafer scale is important for the optimization of epitaxial growth conditions and the design of potential strain relief layers as well as for the understanding of low device yield.

In this work, we present a comparison of polarized stress imaging (PSI) and monochromatic X-ray topography (XRT) for visualizing stress fields and macroscopic defects on full wafer scale of epitaxially grown GaN on Si(111) and sapphire substrates. While XRT allows for a relatively slow measurement of both the substrate and the epitaxial layer individually, PSI is a fast method performed in transmission and always contains integral information. Since both methods are sensitive to the same features but use different imaging methods this comparison helps gaining. a more complete view of wafer defects like stress fields around dislocations, slip lines at the interface between substrate and epitaxial layers or scratches. A detailed analysis of the results from both measurement techniques highlights their respective strengths and limitations in understanding the stress-related properties of the material.

We provide an overview about different types of crystal defects that can be seen in XRT and show how the corresponding stress images measured with PSI appear. Our analysis focuses on the conclusions that can be drawn from the similarities and differences between the images. Particular attention is given to the comparative analysis of the individual XRT measurements of substrate and epi-layer and the PSI image. The results will contribute to the development of industrially relevant high-throughput wafer testing, either as a quality control procedure or to sort out wafers unsuitable for further device processing.

PC-Mon-P8* - Optical and structural characterisation of colour centres in (PVT and PVD synthesized) AlN for quantum applications.

2. Physics and characterization

Amy Albrecht[1]
Jan Beyer[1], Christian Röder[2], Gleb Lukin[2], Andreas Lesnik[2], Sven Besendörfer[2], Sèbastien Pezzagna[3], Tobias Lühmann[3], Marius Wetzel[2], Muhammad Shaheer Khan[1], Johannes Heitmann[1], Jan Meijer[3]
[1] TU Bergakademie Freiberg, Institute of Applied Physics, D-09599 Freiberg, Germany
[2] Fraunhofer Institute for Integrated Systems and Device Technology IISB, D-91058 Erlangen, Germany
[3] Applied Quantum Systems, Felix-Bloch Institute for Solid-State Physics, University Leipzig, D-04103 Leipzig, Germany

Abstract text: Colour centres in wide bandgap materials such as AlN are of growing interest for quantum applications, including qubits, single-photon sources and sensing. Density functional theory (DFT) calculations show that transition metals in combination with vacancy defects form promising colour centres within the bandgap of AlN, potentially forming a triplet ground state [1]. Experimental studies provide promising evidence for the single-photon behaviour of different defect species in AlN [2; 3].
This study presents the optical characterisation of AlN as a host for colour centres on differently grown AlN samples. Wafers from single crystals grown by PVT [4] were investigated with respect to as-grown PL activity and characteristic PL spectra after implantation and annealing. A correlation between the atomic mass of the implanted elements and the increase in PL intensity in the wavelength range 590-620 nm can be observed. This indicates an increase in optically active intrinsic defects (vacancies and vacancy complexes with oxygen), especially when lighter elements were implanted.
AlN films grown on sapphire and silicon substrates by RF magnetron sputtering at different temperatures were investigated for PL activity and film quality.
Optical characterisation was performed using PL and confocal μ-PL. Raman spectroscopy was employed to reveal strain for different regions of the samples whereas XRD measurements revealed structural information for the different growth conditions. From the structural analysis, a correlation between film quality, deposition temperatures and substrate material can be observed. Confocal microscopy images and AFM provide insight into the morphology.

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PC-Mon-P9* - Low-temperature deposition of amorphous AlN thin films on ITO-glass and ITO-PET substrates by rf-sputtering

2. Physics and characterization
Miriam Cadenas[1]
Michael Sun[1], Sirona Valdueza-Felip[1], **Fernando Bernabé Naranjo**[1]
[1] Photonics Engineering Group, University of Alcala, 28871, Alcalá de Henares, Spain

Abstract text: AlN thin films have several applications in optoelectronics and high-power electronics. Fabricating these films using low-temperature processes allows their application to flexible and wearable electronics [1]. This study investigates the properties of AlN thin films deposited by reactive sputtering at room temperature (RT) and 100°C on commercial ITO-glass and ITO-PET substrates. The rf power applied to the Al target, P_{Al}, was varied from 100 W to 175 W with a growth pressure of 0.47 Pa. For comparison, a set of samples was deposited on sapphire in the same run.

X-ray diffraction measurements revealed no peaks related to crystalline AlN for samples deposited on ITO-glass and ITO-PET. On the other hand, energy-dispersive X-ray spectroscopy measurements showed the presence of Al and N in the layers indicating that the films are mainly formed by amorphous AlN. The presence of the AlN layer was also confirmed by cross-sectional scanning electron microscopy measurements which revealed compact and uniform films. The thickness of the layers was estimated by X-ray reflectivity for samples deposited on sapphire, yielding values in the range of 50 to 150 nm.

AlN films exhibited root-mean-square (rms) roughness values (measured by atomic force microscopy) ranging between 4-5 nm and 1.5-3 nm, for ITO-glass and ITO-PET substrates, respectively. In both cases no definitive trend with power was observed, although the lowest rms values are obtained when growing at RT for both substrates.

Optical transmission measurements were conducted to determine the bandgap of the AlN samples deposited on sapphire to avoid the effect of the absorption by the ITO layer. The estimated bandgap was in the range of 5.47 eV to 5.93 eV for all the analyzed samples. These values remained below the theoretical value of crystalline AlN (6.2 eV), which can be related to the presence of defects and electronic states within the bandgap in the disordered structure of the amorphous form, leading to a reduction of the absorption band-edge energy.

These findings demonstrate the feasibility of low-temperature deposition of AlN films on ITO substrates, offering promising results for applications in flexible devices.

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PC-Mon-P10* - Oxidation of AlN surface and interface with GaN analyzed by molecular dynamics simulations

2. Physics and characterization
Yuki Ohuchi[1]
Hiroki Sakakima[2], Satoshi Izumi[2]
[1] Advanced Technology Laboratory, Fuji Electric Co., Ltd., Tokyo 191-8502, Japan
[2] Department of Mechanical Engineering, The University of Tokyo, Tokyo 113-8656, Japan

Abstract text: Improving the performance of GaN-based metal-oxide-semiconductor field-effect transistors (MOSFETs) is strongly desired for next-generation power switching devices. Al diffusion from AlN capping to GaN has been demonstrated to significantly improve channel mobility [1]. Since the low mobility in GaN-MOSFETs has been attributed to the interfacial residual gallium oxide (GaO*x*) [2], the analysis of the oxidized states of AlN and AlGaN has become important for better control of the electrical properties. However, the surface and interface regions are so thin that they have been limited to experimentally analyze. Recent molecular dynamics simulations have enabled us to visualize the microscopic atomic positions of surface oxidized GaN [3]. In this report, we present the results of molecular dynamics simulations of AlN surface oxidation and residual surface GaO*x* on GaN alloying with AlN capping. We have observed reduction of GaO*x* by formation of chemical bonds between Al and O atoms.

A charge-transfer interatomic potential was developed for molecular dynamics simulations. The parameters were fitted to cohesive energies and atomic forces obtained by first-principles calculations for structures associated with oxidations of AlN and AlGaN. Oxidation simulation of AlN with O_2 molecules reproduced the observed surface oxides on an atomic scale [4], indicating the successful adjustment of the interatomic potential.

The Al diffused GaN layer was modeled by annealing a stacked structure of GaN, GaO*x* and AlN layers. GaN/GaO*x* was prepared by oxidation simulation of GaN. The atomic positions were relaxed by high-temperature molecular dynamics simulations. In the relaxed structure after cooling to 10 K, many O atoms are bonded to Al atoms instead of Ga atoms, leading to the reduction of GaO*x* and the formation of AlGaNO*x*. The overlap of the O and Al distributions is in qualitative agreement with the experiment [1]. These O atoms tend to occupy anion sites of a wurtzite crystal, implying the formation of steep interfaces between the Al diffused GaN and dielectric films irrespective of residual GaO*x*.

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PC-Mon-P11* - Carrier Transport Mechanism of Cr-based Ohmic Contacts to Si-doped AlN

2. Physics and characterization

Chao-I (Benny) Liu[1]
Cristyan Quiñones-García[1], Pramod Reddy[2], Seiji Mita[2], Ronny Kirste[2], Ramón Collazo[1], Zlatko Sitar[1]
[1] Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina, USA
[2] Adroit Materials, Cary, North Carolina, USA

Abstract text: Ohmic contacts directly on Si:AlN are typically characterized by high contact resistances and a threshold "knee" voltage owing to a high metal-semiconductor barrier height. This suggests that the conduction mechanism at the metal-semiconductor interface must rely on tunneling to achieve sufficient current injection due to the large barrier height but it could be inhibited by high compensation. In this study, a systematic analysis of T-dependent I-V and TLM was conducted. An equivalent circuit model was developed to understand the carrier transport mechanisms at the metal-semiconductor interface.

Si-doped AlN were grown using MOCVD. The Cr-based Ohmic contact was deposited by e-beam evaporation and annealed at 950°C for 30 seconds in N_2. The room temperature I-V curves exhibited a low voltage threshold of 2V. Resistance for TLM analysis was extracted from the linear regime of the I-V curve and TLM parameters such as R_{sh}=1.3×10^{6}Ω/sq and ρ_c=4.3×10^{-2}Ω-cm^2 were obtained at room temperature. To further investigate the non-linear regime of the I-V characteristics, an equivalent circuit model was developed, which considered Poole-Frenkel emission (PF) and Fowler-Nordheim tunneling (FN) as parallel conduction paths at the metal-semiconductor interface. I-V curve fitting using this model revealed that PF and FN are the dominant conduction mechanisms at lower and higher voltages, respectively. The transition between these mechanisms happens around the voltage threshold observed in the I-V curve. Notably, I_{PF} is T-dependent while I_{FN} is not, therefore, T-dependent measurements were conducted to further explore the contact properties. T-dependent TLM analysis was performed, and R_{sh} and ρ_c at each temperature were extracted. Due to the deep ionization energy of Si:AlN, a significant T dependence of both R_{sh} and ρ_c was observed, with similar E_A~400meV. A minimum ρ_c~1.3×10^{-5}Ω-cm^2 was measured at 200°C, which is 3 orders of magnitude lower than the ρ_c measured at room temperature. The PF plot was constructed and the defect associated with PF emission was identified as an electron trap located 0.5eV below the conduction band. In conclusion, these findings provide insights on carrier injection mechanisms into Si:AlN, while also providing pathways for future investigations aimed at identifying and controlling the defects that facilitate carrier transport in AlN Ohmic contacts.

PC-Mon-P12 - Determination of the bulk refractive index of AlN by spectroscopic ellipsometry

2. Physics and characterization

Imola Urbán[1]
Zsombor Pap[1], Bálint Fodor[1], László Makai[1], **Roland Weingärtner**[2], Sven Besendörfer[2]
[1] Semilab Semiconductor Physics Laboratory Co. Ltd., Budapest, Hungary
[2] Fraunhofer Institute for Integrated Systems and Device Technology IISB, Erlangen, Germany

Abstract text: As an ultra-wide bandgap material with a bandgap of 6.2 eV and excellent thermal conductivity, Aluminum nitride (AlN) is a very promising candidate for future high-frequency and power electronics applications.The refractive index of AlN is a key parameter for various technological applications, from optoelectronics to thermal management. Moreover, a thorough understanding of its optical properties in the widest spectral range is essential for modelling AlN-based structures for further metrology applications.

Former studies on AlN refractive index were carried out on thin layers by spectroscopic ellipsometry [1] and spectroscopic transmission measurements [2], which may differ from the bulk optical properties. In contrast, this study is dealing with the determination of the refractive index of bulk AlN grown by physical vapor transport with very high crystalline quality.Spectroscopic ellipsometry is a highly effective method [3] for measuring the bulk refractive index of Aluminum Nitride.

Spectroscopic ellipsometry is an absolute optical measurement method which measure the change in polarization of light upon reflection form a surface. It is highly sensitive around the Brewster's angle when polarization component in the incident plane (p polarization) vanishes and the phase shift of the two polarization components changes from 0° to 180°. This sensitivity reveals the top surface structure of the sample. For extracting layer thickness and optical properties from the measured spectra a parametric model must be built, and fit must be performed on the parameters to conclude on the actual values describe sample properties. The aim of this study to investigate the bulk AlN optical dispersion from the UV to the IR range, revealing information about the top surface structure as well.For the AlN bulk samples a system of an individual layer on a semi-infinite substrate needs to be assumed to model the data. The substrate is the bulk AlN and exhibits a refractive index of 2.068 and the layer is a near-surface layer of a fitted thickness of 3.3 nm and a refractive index of 1.504. This layer might be related to surface oxide and/or to sub-surface damage due to polishing.

Spatially resolved spectroscopic ellipsometry measurements in comparison to complementary methods as X-Ray Topography will give further insights on the lateral surface structure of the AlN wafers.

PC-Mon-P13* - Searching for Point Defects in Cubic Boron Nitride

2. Physics and characterization

William Stenlund[1]
Joel Davidsson[1], Viktor Ivády[2], Rickard Armiento[1], Igor Abrikosov[1]
[1] Department of Physics, Chemistry and Biology, Linköping University, Linköping, Sweden
[2] Department of Physics of Complex Systems, Eötvös Loránd University, Budapest, Hungary

Abstract text: Searching for Point Defects in Cubic Boron Nitride

William Stenlund1, Joel Davidsson1, Viktor Ivády2, Rickard Armiento1, Igor Abrikosov1

1: Department of Physics, Chemistry and Biology, Linköping University, Linköping, Sweden

2: Department of Physics of Complex Systems, Eötvös Loránd University, Budapest, Hungary

Contact: william.stenlund@liu.se

Cubic boron nitride (c-BN) is a wide-bandgap semiconductor with potential applications in both power electronics and quantum technologies. Point defects have potential applications for single photon emitters and quantum sensors. However, a handful of defects have been identified, and several zero-phonon lines (ZPLs) have been measured in experiments but have not yet been attributed to any specific defect configuration [1]. Recent studies have also suggested point defects with emission in the telecom wavelength [2]. To systematically probe the combinatorially complex chemical space of defects, we generate large-scale point-defect data for c-BN. We apply density functional theory in a high-throughput manner using ADAQ [3] to broadly screen for point-defect complexes containing s- or p-elements. More than 8000 defects have been calculated in different charge and spin states, and their properties are stored in a database, which will be published [4]. In this presentation, we explore this database, focusing on properties such as formation energy, ZPL, and transition dipole moment.

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PC-Mon-P14 - Isotope substitution and polytype control for point defects identification: the case of the ultraviolet color center in hexagonal boron nitride

2. Physics and characterization

Juliette Plo[1]
Anton Pershin[2], Song Li[2], Thomas Poirier[3], Eli Janzen[3], Hannah Schutte[3], Ming Tian[4], Melanie Wynn[5], Samuel Bernard[5], Adrien Rousseau[1], Alexandra Ibanez[1], Pierre Valvin[1], Wilfried Desrat[1], Thierry Michel[1], Vincent Jacques[1], Bernard Gil[1], Agatha Kaminska[6], Neng Wan[4], James Edgar[3], Adam Gali[7], Guillaume Cassabois[1]
[1] Laboratoire Charles Coulomb
[2] HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[3] Kansas State University, USA
[4] Key laboratory of MEMS of Ministry of Education, Nanjing, China
[5] IRCER, Limoges, France
[6] Institute of Physics, PAS, Warsaw, Poland
[7] HUN-REN Wigner Research Centre for Physics, Budapest, Hungary,

Abstract text: Identifying defects is an important goal in condensed matter physics. Once the natures of extrinsic and intrinsic defects are determined, processes to improve the quality and the purity of crystals can be optimized. Conversely, the controlled incorporation of dopants are basic tools for fabricating electronic and optoelectronic devices.

Hexagonal boron nitride (hBN) is a lamellar material, characterized by strong in-plane covalent bindings and weak Van der Waals interactions along the c-axis, leading to the formation of hBN under different stackings, called polytypes. Moreover it has a wide indirect bandgap that allows the existence of several extended and point defects, in particular the deep-level UV emission at 4.1 eV. At low temperature, for natural isotopic abundance in AA'-stacked hBN, the typical photoluminescence (PL) spectrum of the 4.1 eV defect consists in a narrow line around 4.097 eV, called the zero-phonon line (ZPL), corresponding to the emission of a photon without phonon emission and then at lower energy, several phonon replicas located at ~200meV from the ZPL. Today, there is a huge accumulation of experimental and theoretical studies dealing with this UV color center, nevertheless its atomistic origin is still debated. The four most probable structures proposed by theoretical calculations are the carbon dimer, the carbon tetramer, the carbon 6-ring and the Stone-Wales defect (SW) [1,3].

Here we demonstrate that the 4.1 eV emission in hBN comes from the carbon dimer by using isotope substitution and polytype control, with a systematic comparison with DFT calculations. Firstly, we studied the effect of isotopic purification of the host hBN matrix on the PL signal of the 4.1eV defect. This experiment allows us to eliminate the SW defect as a potential candidate and to point out that the phonon replica at ~200 meV originates from a local vibrational mode (LVM) of the defect. Then, by doping samples with carbon and purifying the incorporated carbon (^{Nat}C vs ^{13}C), we have shown that the 4.1eV emission is indeed related to carbon by observing a 6 meV-isotopic shift of the LVM, consistent with the carbon dimer. Finally, by investigating the evolution of the 4.1 eV defect PL lines under hydrostatic pressure for two different stackings, we conclude that the 4.1eV defect corresponds to the carbon dimer.

PC-Mon-P15* - Predicting the elastic properties of boron containing III-Nitride alloys: From ab initio studies to semi-empirical models

2. Physics and characterization

Aisling Power[1]
Cara-Lena Nies[1], Stefan Schulz[1]
[1] Tyndall National Institute, University College Cork, Cork, Ireland

Abstract text: III-nitride materials (AlN,GaN,InN) and their alloys, (Al,Ga,In)N, are widely used in (opto)electronic devices, including LEDs. This stems from their direct band gaps, which, in principle, are tuneable for emission from near infrared to deep ultraviolet. However, in these extreme wavelength regimes, III-N devices suffer from low quantum efficiencies often related to high defect densities which can act as non-radiative recombination centres. The large lattice mismatch, and resulting strain, between the quantum well (QW) active region, barriers and substrate drives the formation of these defects. To address this challenge, recent studies propose introducing wurtzite (WZ) boron nitride (BN) into III-Ns for strain compensation due to its much smaller lattice parameter compared to (Al,Ga,In)N. However, this necessitates detailed understanding on how BN affects the structural, electronic and optical properties of B-III-Ns. Theoretical modelling, such as first principles density functional theory (DFT), are currently widely used to investigate these fundamental properties. Standard DFT implementations, however, are computationally intensive, particularly for accurate band gap descriptions, and are generally limited to small systems (~1000 atoms). To study systems that require a much larger number of atoms for realistic simulation of their properties, such as disordered alloy heterostructures, or to accelerate DFT calculations, semi-empirical models parameterized against DFT are needed. In this work, we develop a simulation framework for B-III-Ns starting with a valence force field (VFF) model. Using DFT data and structural similarities between [111] zincblende and WZ, we establish a semi-analytical approach for determining VFF parameters in binary III-N materials, including WZ BN. Extending this model to B-III-Ns, we examine for instance (B,Ga)N alloys with varying boron compositions. The VFF model predicts structural properties (e.g., bond length distributions) that closely align with DFT calculations. Furthermore, utilising VFF-relaxed atomic positions in DFT electronic structure calculations results in very good band gap agreement (VFF structure vs. DFT structure). Our model can also be used as a basis for further semi-empirical electronic structure models, providing an ideal starting point for large-scale studies, including electronic structures of B-III-N QWs.

PC-Mon-P16 - Bandgap Characteristics of Boron-Containing Nitrides— Ab Initio Study for Optoelectronic Applications

2. Physics and characterization

Pawel Strak[1]
Iza Gorczyca[1], **Henryk Teisseyre**[2]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, 01-142, Warsaw , Poland
[2] Institute of High Pressure Physics, Polish Academy of Sciences, 01-142, Warsaw , Poland; Institute of Physics, Polish Academy of Sciences, 02-668, Warsaw, Poland; Université Côte d'Azur , CNRS, Centre de Recherche sur l'Hétéro-Epitaxie et ses Appli-cations CRHEA , 06-905, Valbonne , France

Abstract text: Hexagonal boron nitride (h-BN) is recognized as a 2D wide bandgap ma-terial with unique properties, such as effective photoluminescence and diverse lattice parameters. Nitride alloys containing h-BN have the potential to revolutionize the electronics and optoelectronics industries. The energy band structures of three boron-containing nitride alloys - $B_xAl_{1-x}N$, $B_xGa_{1-x}N$, and $B_xIn_{1-x}N$ - were calculated using standard density functional theory (DFT) with the hybrid Heyd–Scuseria–Ernzerhof (HSE) functional to correct lattice parameters and energy gaps. The results for both wurtzite and hexagonal structures reveal several notable characteristics, including a wide range of bandgap values, the presence of both direct and indirect bandgaps, and phase mixing between wurtzite and hexagonal structures. The hexagonal phase in these alloys is observed at very low and very high boron concentrations (x), as well as in specific atomic configurations across the entire composition range. However, cohesive energy calculations show that the hexagonal phase is more stable than the wurtzite phase only when $x > 0.5$, regardless of atomic arrangement. These findings provide practical guidance for optimizing the epitaxial growth of boron-containing nitride thin films, which could drive future advancements in electronics and optoelectronics applications.

PC-Mon-P17 - Beta Irradiation Effects on GaN p-i-n Diodes: Unlocking Potential for Betavoltaic Microbatteries

2. Physics and characterization

Noor Alhuda Ahmed AL Saqri[1]
Sofiane Belahsene[2], Dler Jameel[3], Abdelmadjid Mesli[4], Mohammed Henini[5]
[1] Sultan Qaboos University, College of Science, Muscat, Oman
[2] Laboratory for Photonics and Nanostructures, Unité Propre de Recherche, France
[3] University of Zakho, Department of General Sciences, Kurdistan Region, Iraq
[4] Université Aix-Marseille,Institute Matériaux Microélectronique Nanosciences de Provence, Marseille, France
[5] University of Nottingham, School of Physics and Astronomy, United Kingdom

Abstract text: The development of efficient power sources for micro-electro-mechanical systems (MEMS) has driven interest in betavoltaic microbatteries, where GaN stands out due to its wide bandgap (3.4 eV) and high radiation resistance. This study explores the effects of beta particle irradiation (electron energy 0.54 MeV) on the electrical and defect properties of GaN p-i-n diodes grown by Metal Organic Vapor Phase Epitaxy (MOVPE).

Electrical and defect characterization, performed using current-voltage (I-V), capacitance-voltage (C-V), and deep-level transient spectroscopy (DLTS), revealed three electron traps with activation energies of 0.06 eV, 0.18 eV, and 0.81 eV, and a hole trap at 0.83 eV in as-grown samples. Irradiation caused minimal changes to these intrinsic traps but introduced shallow donor defects (0.06 eV to 0.18 eV) near the conduction band on the p-side of the junction.

These shallow defects act as recombination centers, reducing the efficiency of electron-hole pair (EHP) collection, which can degrade betavoltaic device performance. This study highlights the resilience of GaN to high-energy particle exposure while providing insights into defect dynamics critical for optimizing GaN-based betavoltaic applications.

Keywords: GaN p-i-n diodes, beta irradiation, deep-level transient spectroscopy, activation energy, betavoltaic microbatteries.

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PC-Mon-P18* - Random telegraph noise and excess leakage current due to intrinsic defects in p-i-n diodes on GaN-on-Si substrate

2. Physics and characterization

Rajarshi Roy Chaudhuri[1]
Hubert Rockermeier[1], Manuel Stabentheiner[2], Bernhard Ruch[3], Michael Waltl[3], Clemens Ostermaier[2], Dionyz Pogany[1]
[1] Institute for Solid State Electronics, TU Wien, Gusshaustrasse 25, 1040 Vienna, Austria
[2] Infineon Technologies Austria AG, Siemensstrasse 2, 9500 Villach, Austria
[3] Institute for Microelectronics, TU Wien, Gusshaustrasse 25-28, 1040 Vienna, Austria

Abstract text: GaN high electron mobility transistors (HEMTs) for power applications are typically built on Si substrates, resulting in dislocation densities of 1-6×10^9 cm^{-2} within the GaN epitaxial layers [1,2]. The role of dislocations in the electrical properties and reliability of GaN HEMTs is still discussed [1-3]. However, a study of reverse current in quasi-vertical GaN-on-Si p-i-n diodes has revealed that the density of electrically active defects causing an excess leakage current (ELC, i.e. outlier of current distribution) is only about 5×10^3 cm^{-2} [4]. Low-frequency noise spectroscopy, particularly random telegraph noise (RTN), is useful for characterizing intrinsic or stress-induced defects in GaN devices [5-8]. In this work, we investigate RTN and ELC in GaN-on-Si p-i-n diodes and relate them to the presence of active intrinsic defects.

The p-i-n diode is a fundamental part of every gate stack of a normally-off HEMT. Here, an AlGaN barrier (15nm) and uid-GaN (420nm) layer are placed in between the top p-GaN and 1µm thick n-AlGaN at the bottom [4]. Devices with a diameter of 10-75µm have a boron-implanted sidewall to reduce the perimeter leakage.

Two or multi-level RTN, with amplitude ΔI in pA - nA range, is observed at both bias polarizations, mostly in devices having an ELC at reverse bias. The bias dependence of ΔI in both polarizations follows the IV characteristics of the ELC component, attributing thus RTN to fluctuations in ELC. The large relative RTN amplitude, ΔI/I, up to 30% indicates that ELC flows through a constriction related to an extended defect, e.g. closed-core dislocation [4]. Defect- and/or electric field-assisted processes are the origin of ELC. The bias dependence of RTN mean pulse widths (10ms to 10s range) suggests that RTN is due to capture/emission or structural reconfiguration processes on a single point defect which takes part of the extended defect. The work was supported by ALL2GaN EU project no. 101111890.

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PC-Mon-P19* - Confocal Raman and Photoluminescence Characterisation of a GaN-Based LED Chip

2. Physics and characterization
Matthew Berry[1]
Angela Flack[1]
[1] Edinburgh Instruments

Abstract text: Gallium nitride (GaN) is a promising semiconductor for high-power devices due to its superior thermal and electrical properties. Homogeneity is crucial for device performance. Raman and photoluminescence (PL) microscopy are powerful tools for analysing GaN, revealing subtle structural changes across wafers and chips. This poster reports the use of a confocal multimodal microscope to characterise a GaN LED chip.

The LED chip, consisting of GaN-based layers on sapphire with Au bonding pads, was analysed using a 325nm He-Cd laser for PL and a 638 nm laser for Raman. The microscope, equipped with a CCD camera and automated stage, enables spectral mapping.

Raman analysis revealed the E_2 (567 cm^{-1}) and A_1 (LO) (735 cm^{-1}) GaN bands, along with a disorder-activated mode (670 cm^{-1}) and sapphire bands. Raman mapping of the E_2 mode intensity confirmed GaN distribution, with higher intensity in the P- and N-GaN regions. E_2 mode position mapping revealed compressive and tensile strain distribution. Sapphire PL intensity mapping showed diminished PL in high GaN Raman intensity regions.

PL analysis, using 325nm excitation, showed a strong near-band-edge (NBE) emission at 3.41 eV. Other bands were observed at 2.33 eV and 1.71 eV. NBE PL mapping showed a lack of emission in the P-GaN region (consistent with Mg doping effects) and strong emission in the N-GaN region, except in a compressively strained area. 2.38 eV emission, attributed to the InGaN layer, was concentrated at the P-N boundary. UV and green PL spectra from selected points were acquired.

Multimodal microscopy, as demonstrated here, is ideal for GaN device analysis, enabling simultaneous visualisation of strain distribution, GaN and sapphire distribution, and the spatial variation of different luminescent species, providing valuable insights into device quality and performance.

PC-Mon-P20* - Enhancement of water splitting applicability of III-nitride based electrodes by application of surface MXene layers

2. Physics and characterization

Łukasz Janicki[1]
Dominika Majchrzak[1], Detlef Hommel[1], Robert Kudrawiec[1]
[1] Łukasiewicz Research Network – PORT Polish Center for Technology Development, Wrocław, Poland

Abstract text: III-nitrides are one of the materials of choice for water splitting by photoelectrolysis due to their robustness, high chemical stability and the fact that their bandgap straddles the electrochemical potential of water. However, usually the III-nitride based photoelectrolysis setup uses a basic electrolyte due to its higher performance than the acidic one. The chemical reaction of the basic electrolyte with the III-nitride electrode material causes a degradation of the latter due to the photo-assisted etching of the III-nitride surface [1,2]. An application of cocathalysts, acting as an intermediary for carrier transport between the semiconductor electrode and the electrolyte, was proposed to alleviate this issue.

In this work we propose the use of MXenes as cocathalysts for GaN based water splitting electrodes. A set of MXene materials consisting of Cr_2C, Mo_2C, V_2C, V_4C_3, and Ti_3C_2 were applied to the GaN electrode. Each GaN/MXene electrode combination were studied both as-prepared and annealed at 750°C. The application of MXenes to GaN was shown to shift the surface Fermi level towards the valence band resulting in an increased surface barrier for electrons [3]. To test the suitability of MXenes as cocathalysts current-voltage (I-V) characteristics of the photoelectrolysis process were measured revealing the changes in carrier transfer between bare and covered GaN electrode surfces. The I-V curves were measured in intervals of 10 mins to check the chemical stability of the electrodes. The surface morphology of all the electrodes was studied by after the water splitting process to reveal any damage due to photo-assisted etching by scanning electron microscopy.

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PC-Mon-P21 - Comparison of different nitride-based heterostructures prepared by MOVPE for photocatalytic water splitting

2. Physics and characterization

Alice Hospodková[1]
Tomáš Hubáček[1], Markéta Slavická Zíková[1], Halyna Kozak[1], Miroslava Filip Edelmanová[2], Kamila Kočí[2], Jiří Pangrác[1], František Hájek[1], Karla Kuldová[1], Jiří Oswald[1], Michal Palič[1], Filip Dominec[1]
[1] FZU - Institute of Physics, Czech Academy of Sciences, Cukrovarnická 10, 162 00 Prague 6, Czech Republic
[2] Institute of Environmental Technology, Centre for Energy and Environmental Technologies, VSB-Technical University of Ostrava, 17. listopadu 2172/15, 708 00 Ostrava-Poruba,Czech Republic

Abstract text: Hydrogen will play a crucial role in a sustainable energy transition as a long-term energy storage medium. Hydrogen production by water splitting using sunlight is a challenge for the scientific community around the world [1]. The most widely used method is electrolytic water splitting, which makes use of excess photovoltaic energy. Unfortunately, the need for aggressive electrolytes shortens the lifetime of such electrolysers. Alternative methods are photocatalytic (PC) or photoelectrocatalytic (PEC) water splitting. PEC requires an electrolyte to allow efficient transport of ions between the electrodes. The advantage of PC is that no aggressive electrolyte is required, which promises a much longer life for PC equipment. On the other hand, there are much stricter requirements for a suitable photocatalytic material in terms of the energy position of the conduction and valence band edges. InGaN is known as an ideal and unique material for this application, with a suitable conduction and valence band alignment to the redox potentials of water, combined with a low enough band gap to exploit a maximum part of the solar spectrum [2]. For this work we have prepared three sets of samples based on different types of 3D nitride heterostructures by MOVPE: (1) Series A - self-assembled core-shell InGaN/GaN nanorods prepared at different temperatures on sapphire substrate, (2) Series B - top-down etched nanostructures based on thick InGaN layers prepared directly on sapphire, (3) Series C - InGaN/GaN MQW structures prepared on 3D GaN surfaces. These three sets of samples were characterised by photoluminescence, SEM, cathodoluminescence and compared with respect to their efficiency of photocatalytic hydrogen generation using a batch photoreactor. Our results show that the photocatalytic activity is strongly dependent on the material quality, for example influenced by the temperature of the preparation of the InGaN shell around the GaN core. The heterostructures are required to allow fast separation of photogenerated electrons and holes. We will propose different ways of carrier separation for each type of structure A, B and C and compare their efficiency. The problem of reducing the energy losses required for carrier separation will be considered.

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PC-Mon-P22* - Microscopic Raman study of GaN p—n junction diodes grown on OVPE GaN substrates

2. Physics and characterization

Yusuke Hayashi[1]
Kouto Tamamizu[2], Taisuke Ota[2], Shigeyoshi Usami[3], Masayuki Imanishi[3], Yusuke Mori[3], Hirotaka Watanabe[4], Shugo Nitta[4], Yoshio Honda[4], Hiroshi Amano[4]
[1] NIMS, Tsukuba, Japan
[2] ScienceEdge Inc., Suita, Japan
[3] Osaka University, Suita, Japan
[4] Nagoya Univeristy, Nagoya, Japan

Abstract text: Highly conductive GaN substrates grown by a novel oxide vapor phase epitaxy (OVPE) growth method attracts much attention for reducing the on-resistance of vertical power devices compared to conventional hydride vapor phase epitaxy (HVPE) [1]. So far, the realization of carrier concentrations of over 1E20 cm^{-3} and dislocation densities of 1E4 cm^{-2} order have been reported. However, the dislocation properties of killer defects in OVPE-GaN have not been identified. In this study, we report a microscopic Raman study of p-n junction diodes (PNDs) grown on OVPE-GaN substrates, which exhibits an anomalously large strain field near the dislocation core compared to that of PNDs on a HVPE-GaN substrate.

The PND structure was grown by metal organic vapor phase epitaxy (MOVPE) on an OVPE and HVPE-GaN substrate. Vertical PNDs were fabricated using a 500-μm diameter top ring electrode to enable Raman characterization of the PND structures. To include tens of dislocations in a single map, the spatial resolution was 1 μm for mapping PNDs on OVPE and 0.3 μm for mapping PNDs on HVPE and a pre-growth HVPE-GaN substrate (bulk GaN). It has been reported that the E_2^H Raman shift mapping visualizes the dynamic strain change near an edge and mixed dislocation [2], from which the direction and amplitude of the edge component Burgers vector $\boldsymbol{b}$ can be identified using a simulation based on isotropic elastic theory [3]. It is interesting to note that the maximum amplitude of Raman shift in PNDs on OVPE is anomalously large and ×5 to 10 times larger than those of PNDs on HVPE and GaN bulk, indicating that such a large strain is accumulated near the dislocation core. Consequently, the simulation with $\boldsymbol{b} = 1/3\langle 11\text{-}20\rangle = 1\boldsymbol{a}$ approximated the experimental result of PNDs on HVPE and GaN bulk, whereas $\boldsymbol{b} = 1\boldsymbol{a}$ was too small to reproduce the amplitude of Raman shift in PNDs on OVPE. Thus, the simulation indicates that there is a clustering of multiple dislocations at the core with an approximate value of $\boldsymbol{b} = 30\boldsymbol{a}$, which roughly fits the measurement result of PNDs on OVPE.
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PC-Mon-P23* - Electrically Detected Magnetic Resonance and Near Zero Field Magnetoresistance Investigation of Deep Level Point Defects in GaN pn Junction Diodes

2. Physics and characterization

Michael Elko[1]
Artur Solodovnyk[1], Dustin Hassenmayer[1], Patrick Lenahan[1], Yuxin Du[1], Jianan Song[1], Rongming Chu[1], Blair Tuttle[2], David Fehr[3], Joseph Sink[3], Michael Flatte[3]
[1] The Pennsylvania State University, University Park, PA, USA
[2] The Pennsylvania State University, Erie, PA, USA
[3] The University of Iowa, Iowa City, IA, USA

Abstract text: We utilize electrically detected magnetic resonance (EDMR) and near zero field magnetoresistance (NZFMR) to investigate point defects in GaN pn junction diodes. With EDMR and NZFMR, we observe spin dependent recombination (SDR) in the depletion region of pn junction diodes. The dopants are Mg with a concentration of $>10^{19}$ cm^{-3} and Si with a concentration of $5x10^{17}$ cm^{-3}. EDMR is a technique related to electron paramagnetic resonance (EPR), which allows us to glean information about the physical and chemical nature of the defects present in the system [1-3]. However, EDMR and NZFMR are more sensitive and selective than EPR. They are only sensitive to the defects which affect device performance and are able to detect around 1000 total point defects [4], whereas conventional EPR sensitivity is limited to around 10^{10} total defects. NZFMR is a relatively new technique; in principle, it may provide comparable understanding to EDMR.

The EDMR response reported is approximately isotropic, with a g near 2.005. In addition, a weak six-line hyperfine spectrum shown is superimposed upon a much stronger pattern, indicating the involvement of a fairly low abundance spin 5/2 nucleus. This is most likely magnesium. We conclude that we are observing a deep level magnesium coupled defect. The NZFMR response shown does not show clear hyperfine lines, but the broad response suggests unresolved hyperfine interactions.

In the final paper, further EDMR and NZFMR will be presented exploring the angular and temperature dependence of the SDR response of GaN devices. Theoretical analysis will be presented to explain the features observed.

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expressed in this material are those of the author(s) and do not necessarily reflect the views of the United States Air Force.

PC-Mon-P24* - The generation of H_N defects in p-GaN under the influence of temperature and current injection.

2. Physics and characterization

Xuan Liu[1]
E Zhou[2], Xuelin Yang[1], Taiqiao Liu[2], Yingming Song[1], Zhenghao Chen[1], Hongcai Yang[1], Weikun Ge[1], Zhaofu Zhang[2], Bo Shen[1]
[1] School of Physics, Peking University, Beijing, China
[2] The Institute of Technological Sciences, Wuhan University, Wuhan, China

Abstract text: Gallium nitride (GaN)-based electronic devices have exhibited exceptional performance under extreme operational conditions, including high frequency, high power, and elevated temperatures, with p-type GaN being a critical component in PN junctions and p-GaN gate high-electron-mobility transistors (HEMTs). However, Mg-doped p-GaN faces significant challenges, such as a low activation rate of merely 3-4%, attributed to deep donor levels, nitrogen vacancies, and hydrogen-induced self-compensation effects, with the hydrogen concentration in metalorganic chemical vapor deposition (MOCVD)-grown p-GaN remaining as high as 1×10^{18} cm^{-3} even post-activation. To address these issues, this study investigates the lattice occupation and behavior of hydrogen impurities in p-GaN using a c-plane-oriented GaN p-i-n structure fabricated via MOCVD. By applying a forward bias current at varying temperatures for 30 minutes, Fourier transform infrared spectroscopy (FTIR) revealed an infrared-active local vibration peak at 1727 cm^{-1} in the post-bias region, with further c-plane variable polarization angle linearly polarized light FTIR measurements showing no polarization characteristics on the c-plane. Additionally, FTIR spectra with varying incident angles along the c-axis indicated that the vibration intensity of this defect increased with the incident angle, suggesting a vibrational mode aligned with the c-axis, while first-principles calculations predicted an infrared vibration peak for the H_N defects at 1688 cm^{-1}, with vibrations predominantly along the c-axis direction. Based on these results, the defect vibration peak was preliminarily identified as the H_N defects, with the proposed mechanism involving H^+ from the Mg-H complex in p-GaN acquiring two electrons under forward bias and, driven by thermal energy, combining with nitrogen vacancies (V_N) to form a more stable H_N defects. These findings provide a foundational understanding of the dynamic behavior of hydrogen impurities in GaN, offering insights critical for optimizing the performance of GaN-based electronic devices.

PC-Mon-P25 - Controlled wurtzite versus zinc blende phase selection in GaN

2. Physics and characterization

Corentin Guérin[1]
Fabien Jourdan[1], Bruno Gayral[1], Jean-Luc Rouvière[1], Gwénolé Jacopin[2], **Bruno Daudin**[1]
[1] CEA-Grenoble, Grenoble, France
[2] CNRS-Institut Néel, Grenoble, France

Abstract text: The 200 meV band gap difference between wurtzite (WZ) and zinc blende (ZB) GaN and InGaN opens the possibility of realizing homoepitaxial WZ/ZB heterostructures for light emitting devices in the visible and UV wavelength range. However, the realization of such devices requires a controlled conversion at the monolayer scale from WZ to ZB and vice-versa, which has not been achieved to date. In this work, we demonstrate that plasma-assisted MBE grown GaN nanowires (NWs) are offering a new paradigm to control WZ/ZB selection, in particular when grown in the mononuclear growth regime.

In the case of catalyst-grown NWs, the formation of ZB and WZ sections is achieved by controlling the size and the wetting angle of the catalyst droplet. This approach does not hold in the case of GaN NWs, which are grown catalyst-free in plasma-assisted MBE. However, we found that by taking advantage of the mononuclear growth regime of GaN NWs, it is possible to kinetically control the crystallographic variant and to realize ZB insertions of controlled thickness in WZ GaN NWs.

The substrates consist of in-plane organized, MOCVD-grown GaN pedestals [1]. After introduction in the MBE chamber, a ZB GaN section was grown at low temperature and high Ga/N flux ratio. In these conditions, a ZB nucleus of a new layer on top of the GaN pedestal is more stable than its WZ counterpart [2]. Following this single nucleation event, the layer is next rapidly completed, before repetition of this process after an incubation time. Once completed the ZB section, growth was interrupted while temperature was increased and Ga/N flux ratio reduced, to switch to conditions favorable to growth of a WZ upper GaN section. The samples were characterized by hyperspectral cathodoluminescence and photoluminescence spectroscopy. Importantly, no optical signature of stacking faults were found, consistent with high resolution TEM observations. These results assess the kinetically controlled crystallographic WZ/ZB phase selection in NWs as a consequence of the mononuclear growth regime of these nano-objects, opening the path to the realization of full homoepitaxial, carrier confining heterostructures.

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PC-Mon-P26 - Photoluminescence from a- and m-plane GaN:Be,O

2. Physics and characterization

Michael Reshchikov[1]
Kacper Sierakowski[2], Rafal Jakiela[3], Michal Fijalkowski[2], Tomasz Sochacki[2], Denis Demchenko[1], Michal Bockowski[2]
[1] Department of Physics, Virginia Commonwealth University, Richmond, VA 23220, USA
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142, Warsaw, Poland
[3] Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL-02668, Warsaw, Poland

Abstract text: The photoluminescence (PL) from GaN implanted with Be and containing a high concentration of O was investigated. The GaN crystals were grown in non-polar crystallographic directions by hydride vapor phase epitaxy on ammonothermal substrates. After ultra-high-pressure annealing, the Be diffusion profiles, measured by secondary ion mass spectrometry, appeared box-shaped, and the concentration of unintentionally introduced O exceeded that of Be [1]. The defective 700-1000 nm layer was removed to study PL from the region with [Be] » (1-2)×10^{19} cm^{-3} and [O] » (3-10)×10^{19} cm^{-3}. The low-temperature (18 K) PL spectra contained the near-band-edge (NBE) emission and the broad yellow (YL_{Be}) band attributed to the polaronic state of the isolated Be_{Ga} acceptor [2]. The defect-related PL demonstrated all the features observed earlier for Be-doped GaN, such as two-step quenching, the sudden red-shift of the YL_{Be} band at T » 100 K, and the emergence of the ultraviolet (UVL_{Be3}) band at T > 150 K attributed to the shallow state of the Be_{Ga} acceptor [2]. For samples annealed at 1250 °C, the YL_{Be} band was weak, and the NBE band was very strong. From PL studies, the concentration of the isolated Be_{Ga} acceptors was estimated to be ~10^{17} cm^{-3} in such samples. We assume that most of the Be in GaN samples annealed at 1250 °C (~10^{19} cm^{-3}) occupied interstitial sites (Be_i) or formed $Be_{Ga}O_N$ complexes. For samples annealed at 1350 and 1400 °C, the quantum efficiency of the YL_{Be} band approached unity, and the NBE intensity significantly decreased. We estimated that the majority of Be formed the Be_{Ga} acceptors in such samples. We preliminarily propose that the Be_i and the $V_{Ga}O_N$ complexes were abundant after Be ion implantation into GaN with [O] > 3×10^{19} cm^{-3}. At annealing temperatures above 1300 °C, these complexes dissociate, and the Be_{Ga} acceptors are formed from mobile Be_i and V_{Ga}. An interesting effect was observed at 100-120 K. The intensity of the YL_{Be} band increased in all nonpolar GaN samples, while it dropped at these temperatures in all polar (c-plane) GaN:Be [2]. This effect was explained by a higher light-extraction efficiency of PL from optical dipoles parallel to the [0001] axis. This finding confirms the model proposed earlier [2].

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PC-Mon-P27* - Temperature dependent free carrier concentration in GaN:Si by Raman spectroscopy

2. Physics and characterization

Christina Harms[1]
Elias Kluth[1], Jona Grümbel[1], Rüdiger Goldhahn[1], Martin Feneberg[1]
[1] Institut für Physik, Otto-von-Guericke-Universität Magdeburg, Magdeburg, Germany

Abstract text: GaN is already commercialized in a variety of applications. Nevertheless, fundamental questions remain unanswered. A key challenge is the accurate determination of free carrier concentrations, commonly done via the Hall effect. However, Hall measurements depend on electrical contacts. Raman spectroscopy offers a contactless and non-destructive alternative.
Here, we focus on the temperature dependence of the free carrier concentration in GaN doped with Si. We investigate the Raman excitations of hexagonal *c*-plane bulk GaN:Si from 80 K to 300 K. Several samples with Hall-effect-measured carrier concentrations ranging from 10^{12} to 10^{19} cm^{-3} at room temperature were analyzed using Raman spectroscopy with a 532 nm laser excitation.
We determine the frequencies of the coupled phonon-plasmon modes $LPP_{\pm}$ as the maxima of their Raman signals by performing a Lorentzian line-shape fit. Our results reveal that at room temperature, both LPP modes agree with the Hall-effect measurements. Under temperature variation, the LPP_{+} mode shows a weak frequency shift or remains unaffected. Surprisingly, the LPP_{-} mode shifts to higher frequencies with decreasing temperature for all samples, contradicting previous assumptions. Since the $LPP_{\pm}$ resonance frequency is proportional to the carrier density, this would imply an increasing carrier density with decreasing temperature.
A more detailed analysis of the LPP_{-} signal in the Raman spectra requires an evaluation using the dielectric loss function - the imaginary part of the negative inverse dielectric function - which is proportional to the Raman signal. Here, a line-shape fit does not yield the LPP_{-} frequency directly but rather the plasma frequency and its corresponding broadening of the Drude contribution of the dielectric function.
We find that broadening plays a crucial role: if it increases to a state of overdamping, the maximum of the LPP_{-} signal shifts to lower frequencies.
Thus, extracting the carrier density from the LPP_{-} frequency alone is inaccurate. Instead, it must be determined from the plasma frequency obtained via loss function analysis. This correction resolves the apparent contradiction and confirms the expected trend of increasing carrier density with increasing temperature, demonstrating the importance of proper line-shape analysis in Raman-based carrier density determination.

PC-Mon-P28* - Electrical properties and optical deep level transient spectroscopy of GaN with different C doping concentrations

2. Physics and characterization

Momoko Inayoshi[1]
Anna Honda[2], Hirotaka Watanabe[2], Noriyuki Taoka[1], Takeshi Kato[3], Yoshio Honda[3], Wakana Takeuchi[1]
[1] Department of Electrical and Electronic Engineering, Aichi Institute of Technology, Toyota, Japan
[2] Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan
[3] Department of Electronics, Nagoya University, Nagoya, Japan

Abstract text: III-V GaN-based nitride semiconductors are key materials for next-generation power semiconductor devices. Understanding crystal defects that degrade device characteristics is crucial for performance improvement. So far, we have focused on investigating point defects in GaN doped with carbon (GaN:C).[1] However, little experimental data exist from quantitative analysis, especially for GaN:C with different doping concentrations. In this study, we investigated the changes in GaN crystals with different C doping concentrations by optical deep level transient spectroscopy (ODLTS). This method is based on the capacitive transient response of defects with and without irradiation. GaN film was grown on an n-GaN free-standing substrate using metalorganic vapor-phase epitaxy (MOVPE) method. C doping was controlled by adjusting the growth temperatures to 1035, 1015, and 955 °C. C doping concentrations were 1×10^{17}, 1×10^{18}, and 1×10^{19} cm^{-3}, and the samples were named C17, C18, and C19, respectively. ODLTS was measured under light illumination of an LED with a wavelength of 385 nm. Activation energies of traps were then determined from the Arrhenius plot. In this case, activation energy is considered to be the energy from the valence band to the defect position. For C18 and C19, ODLTS spectra exhibited peaks at 130 K, 220 K, and above 300 K, and in C17 at 150 K, 250 K, and above 300 K. The activation energy of hole traps was 0.29 eV at 150K and 0.57 eV at 250K for C17. In C18, the hole traps had activation energy of 0.24 eV at 130K and 0.22 eV at 220K. The hole trap above 300 K had activation energy of 0.16–0.29 eV. It may correspond to the (+/0) charge transition level of C substitution for the nitrogen site (C_N) or a tri-carbon complex. Constant temperature ODLTS was performed for ODLTS spectra above 300K in C19. That showed activation energy of 0.67 eV and 0.52 eV. The 0.67 eV could be attributed to the (0/−) charge transition of C_N (0.9 eV), as well as to C interstitial (C_i) (4+/2+) (0.67 eV) and C_{Ga}–C_N (+/0) (0.70 eV) from the valence band maximum.[2] The 0.52 eV is close to the (+/0) transition of C_N–C_{Ga}–C_N complex at 0.55 eV. These findings suggest that C-related defect types vary with C doping concentration. [1] A. Honda *et al.*, Jpn. J. Appl. Phys., **63**, 041005 (2024). [2] J. L. Lyons *et al.*, Phys. Rev. B, **104**, 075201 (2021).

PC-Mon-P29* - Optimizing GaN-Based Devices through Spectroscopic Ellipsometric Characterization of Thin Films and Layer Structures

2. Physics and characterization

Rebeka Levai[1]
Anna Bolcskei-Molnar[1], Balint Fodor[1], Tibor Suta[1], Peter Basa[1], Attila Suto[1], Ding Yuan Chen[2], David Dai[2], Galia Pozina[2], Anders Lundskog[2]
[1] Semilab Co. Ltd., Prielle K. u. 2, 1117 Budapest, HUNGARY
[2] SweGaN AB, IMA 1, Pursergatan 1, 582 78 Linköping, SWEDEN

Abstract text: In recent years, Gallium-Nitride (GaN)-based devices are key for advancing high-performance optoelectronic and power electronic applications. Thin film thickness and composition control in such devices are essential for manufacturers, as these impact performance and reliability.

In GaN/AlGaN multilayer structures, material properties strongly affects device behaviour, eg.: Al concentration impacts conductivity through 2DEG formation, AlGaN thickness affects leakage currents and conductivity [1], while bandgap energy correlates with electron-hole pair generation. In addition, UV exposure and strong electric fields alter AlGaN/GaN heterostructures [2], occasionally triggering avalanche-induced pair creation [3], influencing device performance.

Spectroscopic ellipsometry (SE) is a non-destructive technique that measures the optical properties and thicknesses of multilayers accurately, fundamental in device efficiency control. This study aims to use SE to characterize the temporal variation of band-gap energy in the AlGaN layer under UV light exposure, yielding an artifact in the measured aluminium (Al) concentration variation. We analyzed AlGaN layers of different thicknesses using industrial spectroscopic ellipsometer under UV illumination for different durations in ionized clean atmosphere environment.

Accurate monitoring boosts efficiency and quality. The experiments were conducted using the Semilab uSE-2300 spectroscopic ellipsometer in collaboration with SweGaN, a SiC/GaN wafer manufacturer.

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PC-Mon-P30 - Investigation of RF Loss Mechanisms and Iron-Doping Memory Effect in N-polar GaN

2. Physics and characterization

Yu Qi[1]
Yu Zhou[1], Qian Li[1], Sheng Cheng[1], Xiaoning Zhan[1], Xinkun Zhang[1], Qingru Wang[1], Jianxun Liu[1], Qian Sun[1], Hui Yang[1]
[1] School of Nano-Tech and Nano-Bionics, University of Science and Technology of China (USTC), Hefei 230026, People's Republic of China

Abstract text: In this work, the mechanism of RF loss up to 110 GHz for N-polar GaN on sapphire grown by MOCVD was stuied in depth for the first time [1]. A CPW transmission line was fabricated on the N-polar GaN surface and measured for S-parameters up to 110 GHz using a vector network analyzer. For more accurate analysis of the RF loss of N-polar GaN buffer, return loss due to the impedance mismatch was considered in practice and absorption loss was introduced to represent the loss of CPW on GaN buffer. With the assistance of S-parameter characterization combined with secondary ion mass spectroscopy analyses, the incorporated oxygen impurity has been identified to be the main source bringing about the severe RF loss of N-polar GaN (48.14 dB/mm @94 GHz). The compensation of Fe-doping in N-polar GaN enables an effective reduction in RF loss. Moreover, the unintentionally doped (UID) GaN layer grown on top of the Fe-doped GaN buffer requires a careful design due to the distinct memory effect of Fe-doping in N-polar GaN, which features a much sharper doping tail of Fe (~ 42 nm/dec) greatly differing from with that of Ga-polar GaN (~ 700 nm/dec). With an optimization of its thickness, a very low RF loss of 0.36 dB/mm at 94 GHz has been attained. Furthermore, by fitting the Fe concentration profile in the UID-GaN according to the mass balance rate equation, it is found that the desorption of Fe on the N-polar GaN surface is significant. A bond-based model is introduced to elucidate the difference of the Fe memory effect between Ga-polar and N-polar GaN. This work provides a useful guidance in growing N-polar GaN HEMT epitaxial structures with low RF loss for high-efficiency W-band power amplifier.

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PC-Mon-P31* - Understanding the impact of stacking fault density on photoluminescence in zincblende InGaN/GaN Quantum Wells

2. Physics and characterization

W. R. Fieldhouse-Allen[1]
D. Dyer[2], M. J. Kappers[3], X. Xu[3], G. Kusch[3], M. Frentrup[3], D. J. Wallis[4], R. A. Oliver[3], D. J. Binks[2]
[1] Department of Physics and Astronomy, University of Manchester, Manchester, U.K.
[2] Department of Physics and Astronomy, University of Manchester, Manchester, U.K
[3] Department of Materials Science & Metallurgy, University of Cambridge, Cambridge, U.K.
[4] Centre for High Frequency Engineering, University of Cardiff, Cardiff, U. K.

Abstract text: InGaN/GaN LEDs grown in the zincblende (zb) phase offer a promising addition to lighting technology currently dominated by wurtzite (wz) phase devices. These zb-LEDs require a lower In % for green emission [1] and could be used with blue wurtzite InGaN/GaN and red InGaAlP LEDs to achieve white lighting. The absence of polarisation fields across zb-QWs when grown in the (001) direction results in recombination lifetimes of about 0.5 ns or less, approximately 100-fold shorter than wz-QWs [1]. This allows more rapid modulation for LiFi communications [2] and reduces the carrier density, delaying efficiency droop until higher drive currents.

The dominant extended defects in zb-GaN are stacking faults (SFs) on each of the four {111} planes [3]. SFs are important to the emission of cubic-based LEDs as they are locations of In segregation [4], impacting the local potential field. The impact of SFs on efficiency and linewidth is significant, as they can influence carrier localisation, radiative recombination rates, and spectral broadening; effects that are crucial for optimising performance.

SFs can annihilate when they intersect [5]; increasing the buffer layer thickness increases the probability of such annihilation. Hence, samples were grown by MOCVD on a [001] 3C-SiC/Si substrate, with GaN buffer layer thicknesses ranging from 600 to 3000 nm. One set of samples contains five quantum wells (QWs), while another set contains only a single QW each. X-ray diffraction and cathodoluminescence data indicate that increasing thickness has reduced the density of wz inclusions and SFs.

Temperature-dependent photoluminescence data were collected indicating an improvement in the high- to low-temperature emission ratio when increasing the buffer layer from 600 to 1500 nm, a modest improvement when increasing to 2300 nm, and no significant difference when further increasing the buffer layer to 3000 nm. The 13 K linewidth is broader at 600 nm, indicating of more inhomogeneity in the sample.

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PC-Mon-P32* - A polytype-transferable empirical-tight-binding parameterization of GaN

2. Physics and characterization

Anh Luan Phan[1]
Daniele Soccodato[1], Alessia Di Vito[1], Alessandro Pecchia[2], **Matthias Auf der Maur**[1]
[1] Department of Electronic Engineering, University of Rome "Tor Vergata", Rome, Italy
[2] CNR-ISMN, Consiglio Nazionale delle Ricerche, Monterotondo, Italy

Abstract text: Empirical tight-binding (ETB) is a widely used theorical method, offering a balance between computational cost and accuracy. However, the ETB models rely on high-quality parameter sets, whose key indicator is the transferability. Traditionally, for tetrahedrally bonded materials, an ETB scheme developed by Jancu et al. has been commonly used. While widely adopted, it has limitations, particularly in handling strain and in transferability across different material systems which stem from the lack of corrections accounting for changes in the local atomic environment. A more recent ETB scheme by Tan et al. offers an advancement by introducing corrections that explicitly depend on the local environment. This new scheme has been shown to be superior to Jancu's one when dealing with disordered alloys. Given that, we anticipate similar advantages for the polytype transferability. In fact, it was pointed out that Jancu's parameterization fitted to one crystal phase (zincblende or wurtzite) are poorly transferred to the other phase, posing challenges for simulating, e.g. polytypic GaN wurtzite-zincblende heterostructures. However, Tan et al. did not provide III-nitride parameters, requiring other researchers to perform the parameterization by themselves. Therefore, here we present a new parameterization of GaN that is transferable between the two phases.

We validated the transferability of our newly obtained GaN parameter set by comparing the ETB band structures of GaN in both zincblende and wurtzite phases with the corresponding hybrid-functional density functional theory (DFT) calculations. The matching is good in both cases, although we did not include any wurtzite targets in the fitting process. Even the resulting valence band offset between the two crystal phases also agree very well with the experiment. For further assessment, we applied the obtained GaN parameters to the case of the minimal GaN wurtzite-zincblende superlattice (the stacking order is ABACB in Ramsdell notation). It turned out that our ETB superlattice band structure shows very good agreement with the hybrid-functional DFT one, except for a slight underestimation of the band gap. The fact that our GaN parameters can reproduce equivalently well the band structures of both GaN crystal phases as well as that of the polytypic superlattice proves the effectiveness of our parameterization procedure.

PC-Mon-P33* - Giant Raman scattering by a GaN phonon-polariton

2. Physics and characterization

Mayssoune MINA[1]
[1] LCP-A2MC, Lorraine University, METZ, France

Abstract text: MINA Mayssoune [1], ALHADDAD Toni, PAGES Olivier
LCP-A2MC, UR 4632, Université de Lorraine, 57000 Metz, France
[1] mayssoune.mina@univ-lorraine.fr

The III-V GaN semiconductor compound with wurtzite (hexagonal) structure exhibits a large bandgap (3.4 eV), making it a model system to explore the phonon-polariton coupling by near-forward Raman scattering (schematically done in "transmission") in the visible spectral range. Four atoms per primitive cell generate 12 normal vibration modes at the center of the Brillouin zone, where Raman scattering operates due to the quasi-vertical dispersion of the light probe [1]. We focus on the polar optical modes A_1 and E_1 due to cation vs. anion vibrations along the singular **c**-axis and perpendicular to it, respectively. Such modes are likely to support the phonon-polariton coupling if sufficiently large (photon-like) wavelengths can be addressed, justifying the near-forward scattering geometry [1].
Our near-forward Raman setup is operated with a fixed detection (at the top of the crystal) and a variable incidence (at the bottom), differing from earlier used setups in the literature involving a fixed incidence and a variable detection [2-4]. We report near-forward Raman spectra at near-normal incidence/detection across thick GaN monocrystals with in-plane **c**-axis in parallel (A_1) and crossed (A_1+E_1) polarizations of the incident and scattered light addressing specific A_1 and/or E_1 symmetries, as specified in brackets. At nearly minimal laser incidence corresponding to in-plane propagation of the lattice vibrations, the phonon-polariton Raman signal is dramatically enhanced, suggesting the possibility of a high-speed (photon-like) transfer of information massively supported by the crystal (phonon-like).
The discussion is supported by experimental (at various scattering angles) and theoretical (based on a calculation of the phonon-polariton Raman cross section within a linear dielectric approach [5]) studies of the ordinary A_1 and E_1 phonon-polariton dispersions, and of the extraordinary A_1-E_1 phonon dispersion.

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PC-Mon-P34* - Characterizations of in-gap states in heavily doped GaN layers and a 25-nm-thick GaN-based tunnel junction

2. Physics and characterization

Daichi Imai[1]
Motoki Kondo[1], Kazuki Osada[1], Raiya Hirose[1], Hinata Uda[1], Tetsuya Takeuchi[1], Takao Miyajima[1]
[1] Meijo University, Nagoya, Japan

Abstract text: GaN-based tunnel junctions (TJs) have attracted much attention as an alternative to highly resistive hole-injection layers in Al(Ga)N-based optoelectronic devices.[1,2] A thin depletion layer, formed by an abrupt interface between heavily doped n- and p-type layers, is favorable for obtaining low resistance TJs by enhancing the tunneling probability. Conversely, the resistivity of GaN-TJs decreases with increased overlap between the Si donor and Mg acceptor profiles.[1] Current conduction via in-gap states, e.g., hopping conduction, has been suggested as the cause of this low-resistivity.[1,2] However, electrical characterization of in-gap states (e.g., C-V, DLTS) is challenging due to tunnel current conduction under reverse-bias. In this study, we investigate in-gap states in a thin GaN-TJ using photothermal deflection spectroscopy (PDS), a highly sensitive method for detecting optical absorption via in-gap states, to elucidate the current conduction mechanism in low-resistance GaN-TJs.

A 25-nm-thick GaN-TJ, comprising 15-nm-thick n^{++}-GaN and 10-nm-thick p^{++}-GaN, was grown on an undoped-GaN/sapphire template using metal-organic vapor-phase epitaxy.[1] The designed Si and Mg concentrations were 6.0×10^{20} and 3.0×10^{20} cm^{-3}, respectively. As references, a 15-nm-thick n^{++}-GaN and a 10-nm-thick p^{++}-GaN on a GaN template were also prepared. Additionally, 100-nm-thick n^{++}- and p^{++}-GaN layers on a GaN template were fabricated to investigate the origin of PDS signal from the thin GaN-TJ.

The room-temperature PDS signal intensity (S_{PDS}), spanning from below the GaN band-edge to 2.6 eV, exhibited a significant increase in the GaN-TJ sample. In contrast, those of the n^{++}- and p^{++}-GaN samples showed no increase compared to the reference GaN template, indicating that the formation of the TJ significantly increased the density of in-gap states. In the GaN-TJ sample, the optical absorption via in-gap states was estimated to be up to 70 times higher than in the GaN template. Additionally, in the 100-nm-thick n^{++}- and p^{++}-GaN samples, the n^{++}-GaN exhibited a higher S_{PDS} than the p^{++}-GaN below the GaN band-edge. This suggests that n^{++}-GaN plays a greater role in the formation of in-gap states in GaN-TJs than p^{++}-GaN.

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PC-Mon-P35* - GaN Surface Passivation by Two-Dimensional Materials Coating

2. Physics and characterization

Danxuan Chen[1]
Jin Jiang[2], Thomas F. K. Weatherley[1], Jean-François Carlin[1], Mitali Banerjee[2], Nicolas Grandjean[1]
[1] Laboratory of Advanced Semiconductors for Photonics and Electronics, Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland
[2] Laboratory of Quantum Physics, Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Abstract text: Conventional semiconductors often feature surface states (SSs) that act as non-radiative recombination centers (NRCs), which can negatively impact their optical performance. However, when these semiconductors are coupled with two-dimensional **(**2D) materials in hybrid van der Waals heterostructures, their surface electronic structure could be altered; charge transfer could occur through tunnelling or hopping, which could passivate the SSs. In this study, we investigated the optical properties of a series of surface GaN/AlGaN quantum wells (QWs) with varying nanometer-scale surface barrier thickness, d = 0 to 15 nm [1]. Thanks to the reduced surface recombination rate of III-nitride semiconductors, a high cathodoluminescence (CL) intensity was observed at room temperature, even from the uncapped QW (d = 0). However, the QW CL intensity increases nonlinearly with d, indicating the non-negligible impact of deep traps near the c-plane III-nitride surface. We then deposited few-layer MoS_2 flakes on the surface GaN QWs and found that the presence of MoS_2 strongly enhances the light emission from the uncapped QW. Our results suggest that the primary role of MoS_2 is to passivate intrinsic SSs at the GaN surface, mitigating the limiting effect of NRCs caused by surface crystal termination. Overall, this work demonstrates the efficient passivation of III-nitride surfaces by 2D materials coatings, which could be leveraged to advance the development of micro- and nanoscale optoelectronic devices with a high surface-to-volume ratio, including micro-LEDs.

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PC-Mon-P36 - Characterization of Mg-Implanted GaN Layers for Vertical Power Devices Using UV-Assisted KPFM

2. Physics and characterization

Jesús Ortiga-Fibla[1]
Núria Garro[1], Sonia Murcia-Mascarós[1], Frank Torregrosa[2], Stéphane Morata[2], Ina Ostermay[3], Enrico Brusaterra[3], Eldad Bahat-Treidel[3], Sondre Michler[4], Vesselin Donchev[5], **Ana Cros**[1]
[1] Institute of Materials Science (ICMUV), University of Valencia, Valencia, Spain
[2] Ion Beam Services (IBS), Peynier, France
[3] Ferdinand Braun institute (FBH), Berlin, Germany
[4] Siltronic AG, München, Germany
[5] Faculty of Physics, Sofia University, Sofia, Bulgaria

Abstract text: Achieving high breakdown voltages in GaN vertical devices is critical for the next generation of power electronics. This requires precisely engineered p-type doped regions for which Mg ion implantation and rapid thermal annealing are the leading techniques. However, defect formation and limited acceptor activation—especially in heteroepitaxial GaN—often result in highly resistive layers that hinder conventional characterisation, such as the Hall effect. This challenge underscores the need for more advanced and innovative approaches.

In this study, we provide a comprehensive characterization of Mg-implanted GaN layers grown on Si, compared to p-type doped layers designed for vertical power transistors. Ion implantation was conducted at room temperature and 500 °C, with doses ranging from 2.5 to 20 × 10^{14} cm^{-2}. Pulsed rapid thermal annealing at 1250 °C was employed for Mg activation, with the surface protected by a dual cap layer of SiN_x and Al_2O_3. We employ ultraviolet light-assisted Kelvin probe force microscopy (UV-KPFM) to investigate doping by analyzing surface potential (SP) and surface photovoltage (SPV) with high spatial resolution. Upon illumination, electron-hole pairs are created and immediately separated by the surface electric field. Depending on the polarity of the carriers moving to the surface, the resulting band flattening leads to positive or negative SPV. The evolution of SPV with illumination power provides insights into carrier dynamics and surface band bending.

Our results reveal significant differences which correlate with implantation dose and surface defects. One of the implanted samples exhibited n-type behaviour, while those implanted at higher doses showed p-type polarity. When present, surface defects act as hole traps, limiting SPV and compromising electrical homogeneity. Additionally, we identify acceptor segregation in a highly doped (~10^{20} cm^{-3} [Mg]) p-type sample, revealing 2 nm higher regions with 250 times increased doping.

These findings highlight UV-KPFM's potential for characterizing Mg-doped and Mg-implanted GaN, aiding the advancement of efficient GaN vertical power devices.

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PC-Mon-P37 - Quantitative Analysis on Thermal Resistance of GaN-on-Si Materials Through Structure Function and Pulsed I-V Methods

2. Physics and characterization

Qingru Wang[1]
Yu Zhou[1], Quan Dai[2], Xiaoning Zhan[1], Jianxun Liu[1], Qian Li[1], Xinkun Zhang[1], Qian Sun[1], Hui Yang[1]
[1] School of Nano-Tech and Nano-Bionics, University of Science and Technology of China, Hefei 230026, P. R. China
[2] Key Laboratory of Semiconductor Display Materials and Chips, Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, Suzhou 215123, P. R. China

Abstract text: One of the major challenges in the commercialization of GaN-on-Si RF HEMTs is the high thermal resistance introduced by the AlN/AlGaN multi-layer buffer, which significantly affects device performance and reliability. In this study, the structure function method was employed to precisely determine the intrinsic thermal resistance of different GaN-on-Si buffer structures by constraining the heat flow along one-dimensional pillar structures formed by etching process. A temperature sensor chip was designed with a heat source layer, and a temperature sensor composed of Schottky diodes. Three buffer configurations were investigated: (1) a single-layer AlN buffer, (2) an AlGaN/GaN superlattice (SL) buffer, and (3) a step-graded AlGaN buffer. The results reveal that the single-layer AlN buffer exhibits the lowest thermal resistance, with an extracted thermal resistance value (R_{th}) of 5.83×10^{-8} m²K/W, compared to 7.18×10^{-8} m²K/W for the SL buffer and 9.36×10^{-8} m²K/W for the step-graded buffer.

To further investigate the impact of GaN buffer layer design on device-level thermal behavior, static-pulsed I-V measurements (pulsed width=300 ns and 100 us) were applied on two-terminal test structures with varying GaN buffer thicknesses (t_{GaN}=0.8 μm, 1.0 μm, 1.3 μm, and 1.8 μm). The Ohmic contacts of the two-terminal devices were formed using regrown n^{++}GaN, achieving a contact resistance of 0.15 Ω·mm, ensuring that the majority of heat source originates from the channel. The extracted thermal resistance values showed that the optimal thermal dissipation occurred at a GaN buffer thickness of 1.0 μm for devices with a heat source length of 8-20 μm. The results suggest that both vertical and lateral heat dissipation pathways play critical roles in determining the overall thermal resistance. In particular, excessively decreasing the GaN buffer thickness leads to increased thermal resistance due to limited lateral heat spreading. The findings offer valuable insights for optimizing the thermal management of GaN-on-Si RF HEMTs from the perspective of material, providing a way for improved device performance and reliability.

PC-Mon-P38* - Understanding GaN Island Formation for Advancing the Growth of GaN on AlScN and AlYN by Metal-Organic Chemical Vapor Deposition

2. Physics and characterization

Niklas Wolff[l]
Isabel Streicher[2], Oliver Rehm[3], Teresa Duarte[4], Martina Müller[3], Stefano Leone[4], Lorenz Kienle[1]
[1] Kiel University, Department of Material Science, Kiel Germany
[2] Consiglio Nazionale delle Ricerche - Istituto per la Microelettronica e Microsistemi, Catania, Italy
[3] Konstanz University, Department of Physics, Konstanz, Germany
[4] Institute for Applied Solid State Physics (IAF), Freiburg, Germany

Abstract text: Recently, the growth Sc- and Y-doped AlN layers by Metal-Organic Chemical Vapor Deposition (MOCVD) and their integration into gallium nitride (GaN)-based heterostructures have been explored assessing possible applications as barrier layers in high-electron mobility transistors (HEMT).[1-3] To this end, the integration of silicon nitride (SiN) caps has propelled the performance of AlScN-GaN HEMTs, yet the growth of an optimized GaN cap on AlScN remained a challenge as GaN was observed to grow preferentially in islands.[4]

In this work, we advanced the growth of conformal GaN layers on Sc- and Y-doped AlN barriers emphasizing its potential to unlock superior device performance and significantly reduce ohmic contact resistance compared to SiN counterparts.

Nano- and chemical structure investigations were performed to understand the origin of island formation, leading to process parameter optimization. Analytical Scanning Transmission Electron Microscopy (STEM) and hard X-ray photoelectron spectroscopy (HAXPES) studies were performed on all-nitride SiN_x capped and GaN capped $Al_{0.94}Sc_{0.06}N$ and $Al_{0.94}Y_{0.06}N$ layers, demonstrating chemical concentration gradients.

Based on these insights, optimization of process parameters resulted in conformal layers of GaN, avoiding oxidation of the barrier layer. These achievements add to the progress on the development of novel HEMT structures containing Sc- and Y doped AlN barrier layers.

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PC-Mon-P39 - Estimating ABC recombination coefficients by time-resolved cathodoluminescence – a method and examples

2. Physics and characterization

Konrad Sakowski[1]
Łukasz Borowik[2], Névine Rochat[2], Pawel Kempisty[1], Pawel Strak[1], Natalia Majewska[3], Sebastian Mahlik[3], Kamil Koroński[4], Tomasz Sochacki[1], Jacek Piechota[1], Marc Fouchier[5], Agata Kaminska[1], Stanislaw Krukowski[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142 Warsaw, Poland
[2] Univ. Grenoble Alpes, CEA, Leti, F-38000 Grenoble, France
[3] Institute of Experimental Physics, Faculty of Mathematics, Physics and Informatics, University of Gdansk, Wita Stwosza 57, 80-308 Gdansk, Poland
[4] Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, 02-668 Warsaw, Poland
[5] Attolight AG, EPFL Innovation Park, Building D, 1015 Lausanne, Switzerland

Abstract text: Time-resolved cathodoluminescence (TRCL) is a new and actively developed experimental technique, which can be used for the characterization of semiconductor bulk material and heterostructures. The distinctive advantage of this method is its spatial resolution, as it accounts for nanometer-scale measurements, which makes it possible to characterize the local properties of semiconductor material. We would like to present a numerical framework for determination of ABC recombination coefficients based on TRCL results [1]. This method is devoted to determine the parameters of the distinctive recombination processes (SRH, radiative, Auger) contributing to recombination as well as the proportions of their contribution to the total recombination rate. The method is based on the introduction of instantaneous decay rate and expressing it as a function of normalized optical emission intensity. Then, by polynomial coefficients fitting it is possible to estimate recombination constants for low- and high-excitation regimes. The method was first introduced for time-resolved photoluminescence [2]. It is implemented in an open-source numerical library *logpli* [3].

We will show what are the foundations of this method for estimating ABC recombination parameters. Usage, capabilities and challenges will be discussed. Examples of application of this framework to estimate sub-surface recombination parameters of a gallium nitride sample will be shown. In particular, it will be demonstrated that recombination parameters may vary within the same sample depending on location or depth.

PC-Mon-P40* - Near field investigation of surface plasmon phonon polariton launch on n-GaN surface

2. Physics and characterization

Vytautas Janonis[1]
Adrian Cernescu[2], Pawel Prystawko[3], Simonas Indrišiūnas[1], Irmantas Kašalynas[1]
[1] Center for Physical Sciences and Technology, Vilnius, Lithuania
[2] Attocube Systems AG, Munich, Germany
[3] Institute of High Pressure Physics, Warsaw, Poland

Abstract text: Polaritonic excitations at the material interfaces have been shown to offer possibilities for control of light, while taking advantage of the properties of the supporting material. While numerous possible variations of polaritonic excitations are possible [1], in this work we investigate the propagation range of hybrid surface plasmon-phonon polaritons (SPPhPs) on the surface of heavily doped n-GaN crystal. The n-GaN semiconductors allowed the observation of hybrid quasiparticles composed of plasmonic and phononic oscillations in high quality crystalline lattice under usage of relatively strong doping [2]. The SPPhPs excited on the surface of n-GaN gratings demonstrated in a far field the narrow spectrum and directional thermal radiation patterns, indicating on a high temporal and spatial coherence of the hybrid polaritons, which is expected to exhibit coherence length values of up to 9 mm under normal conditions [3].

In this work a direct imaging of hybrid SPPhPs propagation in n-GaN was performed for the first time to the best of our knowledge [4]. Scattering-type scanning near-field optical microscopy was utilized to measure the distribution of electrical fields provided by hybrid SPPhPs launched near the surface relief grating at two selected frequencies of 920 cm^{-1} and 570 cm^{-1}. The experimental data were compared with Finite Difference Time Domain (FDTD) simulations carried out in *CST Studio Suite*. All results were found to be in good agreement providing us with additional physics insights on hybrid SPPhP excitation and large distance propagation. We believe that our results pave the way toward new practical applications of hybrid polaritonics which can be also integrated with other nitride-semiconductor interfaces.

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PC-Mon-P41* - Recent advances in detection of atmospheric elements (H, C, O) in gallium nitride (GaN) via dual beam depth profiling with ToF-SIMS

2. Physics and characterization

Patrik Straňák[1]
Tomasz Sochacki[2], Robert Kucharski[2], Michal Bockowski[2], Lutz Kirste[1]
[1] Fraunhofer Institute for Applied Solid State Physics IAF, Tullastrasse 72, 79108 Freiburg, Germany
[2] Institute of High Pressure Physics (UNIPRESS), Polish Academy of Sciences, Sokołowska 29/37, 01-142 Warsaw, Poland

Abstract text: Measuring carbon (C), oxygen (O), and hydrogen (H) impurities in Gallium Nitride (GaN) is crucial for ensuring the material's quality and optimal electrical properties. Low impurity levels are essential for the reliable performance of various applications, including vertical devices such as power transistors, high-frequency amplifiers, and optoelectronic components like LEDs and laser diodes. High concentrations of these atmospheric elements can lead to damaging effects such as increased defect densities, reduced carrier mobility, and compromised electrical properties, which may ultimately result in device failure or inefficiency [1]. Traditionally, dynamic secondary ion mass spectrometry (SIMS) has been utilized for this purpose due to its ability to achieve low detection limits. This effectiveness stems from the continuous sputtering process, which minimizes the redeposition of atmospheric elements during analysis.

In this work, we present recent advances in Time-of-Flight (ToF) SIMS optimized for the detection of low levels of C, O, and H impurities in GaN. The optimization process employed implanted GaN, allowing for a tailored approach to improve detection limits. Despite the inherent duty cycle limitations of ToF-SIMS, our latest results indicate that background levels can be significantly reduced, approaching those of dynamic SIMS, by utilizing a high sputtering rate in dual-beam ToF-SIMS.

This procedure has been applied to compare impurity levels across various GaN substrates, providing valuable insights into the impact of analyzed impurities on material quality [2]. Presented advancements in ToF-SIMS sensitivity enhance the refinement of material processing techniques in high-reliability GaN applications.

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PC-Mon-P42 - Spontaneous and piezoelectric polarization: basic formulation implemented in ab initio approach to nitride wurtzite and zinc blende structures

2. Physics and characterization

Konrad Sakowski[1]
Pawel Strak[1], Pawel Kempisty[2], Jacek Piechota[1], Izabella Grzegory[1], Eva Monroy[3], Agata Kaminska[4], Stanislaw Krukowski[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142 Warsaw, Poland
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142 Warsaw, Poland & Research Institute for Applied Mechanics, Kyushu University, Fukuoka 816-8580, Japan
[3] Univ. Grenoble-Alpes, CEA, Grenoble INP, IRIG, PHELIQS , 17 av. des Martyrs, 38000 Grenoble, France
[4] Cardinal Stefan Wyszynski University, Faculty of Mathematics and Natural Sciences. School of Exact Sciences, Dewajtis 5, 01-815 Warsaw, Poland

Abstract text: Fundamental properties of spontaneous and piezoelectric polarization are reformulated. It was shown that Landau definition of polarization as a dipole density could be used to the infinite systems. The difference between the bulk polarization and surface polarity are distinguished thus creating clear identification of both components. This identification is in agreement with numerous experimental data – emission energy red-shift presence and absence for wurtzite and zinc blende multiquantum wells (MQWs), respectively. The local model of spontaneous polarization was created and used to calculate spontaneous polarization as the electric dipole density. The proposed local model correctly predicts c-axis spontaneous polarization values of the nitride wurtzite semiconductors. In addition, the model results are in accordance with polarization equal to zero for zinc blende lattice. The spontaneous polarization values obtained for all wurtzite III-nitrides are in basic agreement with the earlier calculations using Berry phase. Wurtzite nitride superlattices *ab initio* calculations were performed to derive polarization-induced fields in the coherently strained lattices showing good agreement with the experimentally determined polarization values. The strained superlattice data were used to determine the piezoelectric parameters of wurtzite nitrides obtaining the values that were in basic agreement with the earlier data. Zinc blende superlattices were also modeled using *ab initio* calculations showing results that are in agreement with the absence of polarization of all nitrides in zinc blende symmetry.

PC-Mon-P43* - Unraveling the stress evolution behavior induced by impurity incorporation in Ge-doped GaN bulk single crystals grown by Na-flux method

2. Physics and characterization

Zhiwei Si[1]
Zongliang Liu[2], Xiaoming Dong[3], Mengya Li[2], Xiaohui Peng[3], Tao Zhang[3], Jiafan Chen[3], Ke Xu[3]
[1] Information Materials Research Department, Suzhou Laboratory, Suzhou 215123, Jiangsu, China
[2] Shenyang National Laboratory for Materials Science, Jiangsu Institute of Advanced Semiconductors, Suzhou 215123, Jiangsu, China
[3] Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, Suzhou 215123, Jiangsu, China

Abstract text: Gallium nitride (GaN) can be effectively modulated electrically through germanium (Ge) doping, which has great advantages in RF and power device applications. At present, there is a lack of systematic research on the impurity incorporation behavior, optical properties and stress evolution behavior induced by Ge doped GaN bulk single crystal. Controlling impurity incorporation is critical for device performance enhancement. In this paper, the distribution of deep energy level defects along the growth direction and the evolution behavior of stress along the growth direction of Ge-doped GaN are systematically investigated. A three-dimensional growth mode was observed for the first time in Na-flux GaN with low Ge feedstock ratios using cathodoluminescence microscopy, and a link between the growth mechanism, defect distribution and stress evolution behavior was established. The growth structure of the growth interface between seed crystals and Na-flux GaN is investigated in detail, and the appearance of voids and dislocations can effectively release the compressive stresses on the growth interface due to the lattice mismatch between the seed crystals and the grown Na-flux GaN. Moreover, the tensile stress introduced by the high-density three-dimensional growth mode at the early stage of growth can rapidly reduce the interfacial compressive stress. By further increasing the Ge dopant ratios, Ge may act as a surfactant to reduce the probability of the appearance of three-dimensional growth modes and the density of pits, thus modulating the crystal stress evolution, and optical properties.

PC-Mon-P44 - Spontaneous polarity inversion in GaN driven by a calcium monolayer under near-equilibrium growth

2. Physics and characterization

Xiaohui Peng[1]
Zongliang Liu[2], Xiaoming Dong[1], Tao Zhang[1], Zhiwei Si[3], Ke XU[1]
[1] Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, Suzhou, 215123, Jiangsu, China
[2] Shenyang National Laboratory for Materials Science, Jiangsu Institute of Advanced Semiconductors, Suzhou, 215123, Jiangsu, China
[3] Information Materials Research Department, Suzhou Laboratory, Suzhou 215123, Jiangsu, China

Abstract text: Polarization engineering—tailoring polarization fields and band structures in III-nitride heterointerfaces—enables breakthrough performance in electronic and photonic device. Achieving atomically homogeneous polarity inversion, however, remains a fundamental challenge, with its underlying atomic-scale mechanisms still elusive. Here, near-thermodynamic equilibrium growth of GaN routinely exhibits spontaneous polarity inversion, wherein interfacial energy minimization provides a unique avenue to probe the inversion mechanisms. HRTEM reveals a coherent calcium monolayer (ML-Ca) at the GaN interface, inducing an abrupt N-to Ga-polarity transition. Such self-assembly mechanism is inferred from spatially correlated growth striations and asymmetric defect distribution across the interface. Furthermore, first-principles calculations identify charge transfer from the calcium interlayer to opposing GaN matrices, leading to localized bandgap narrowing and interfacial confinement of the two-dimensional electron gas (2DEG). This work uncovers the atomistic origin of spontaneous polarity inversion in III-nitrides and establishes a transformative design framework for the heterogeneous integration of high-performance optoelectronic and power device.

PC-Mon-P45 - Measurement of the Dielectric Constant of GaN thin films at MHz to GHz Frequencies

2. Physics and characterization

Surender Subburaj[1]
Roberto Quaglia[1], Menno J Kappers[2], Rachel A Oliver[2], **David J Wallis**[3]
[1] Centre for High Frequency Engineering, University of Cardiff, Cardiff, U. K.
[2] Department of Materials Science & Metallurgy, University of Cambridge, Cambridge, U.K.
[3] Centre for High Frequency Engineering, University of Cardiff, Cardiff, U.K. and Department of Materials Science & Metallurgy, University of Cambridge, Cambridge, U.K.

Abstract text: The last 30 years has seen a rapid development of GaN device technologies with the utility of GaN now second only to Silicon. Commercial GaN devices are currently found in a large range of applications form solid state lighting [1], through mobile phone and laptop chargers [2] to RF communication systems [3]. GaN devices are also being developed for visible light communication where GaN LEDs have been demonstrated with switching speed in the GHz frequency range [4].

A fundamental parameter which impacts the performance of devices is the dielectric constant which despite its name is frequency dependent. For hexagonal GaN the dielectric constant is reasonably well defined at low frequencies (DC to kHz) [5] and at THz and optical frequencies (»10^{14} Hz) [6], but to the best of our knowledge no measurements of the dielectric constant exist in the technologically important frequency range where most devices operate, i.e. in the MHz to GHz frequency range.

In this paper we present results for the measurement of simple GaN capacitor structures in the frequency range 10 MHz to 67 GHz. The complex impedance of such capacitors, with varying sizes between 350 μm and 20 μm diameter, was measured using small-signal conditions by means of scattering parameters using a vector signal analyser (VNA). The data is then fitted using a simple LCR (Inductance, Capacitance, Resistance) model to extract the capacitance of the different size structures. The capacitance is seen to vary exactly as expected with the device area, allowing the dielectric constant of GaN parallel to the c-axis to be accurately estimated. The results indicate that the dielectric constant is in fact constant over this frequency range, within the error of the measurements, with a value of 10.4.

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PC-Mon-P46* - Probing Fermi Energy and Temperature-Dependent Shifts in Doped Homo-Epitaxial GaN Layers Using Micro-Raman Spectroscopy

2. Physics and characterization

Aomar Ezza[1]
Denis Machon[1], Camille Sonneville[2], Ali Soltani[1], Andreas Ruediger[3], Eric Frayssinet[4], Yvon Cordier[4], Dominique Planson[2], Hassan Maher[1]
[1] Laboratoire Nanotechnologies Nanosystèmes (LN2)-IRL3463, CNRS, Université de Sherbrooke, INSA Lyon, Université Grenoble Alpes, École Centrale de Lyon, Sherbrooke, J1K 0A5 Québec, Canada
[2] Université Lyon, INSA Lyon, Université Claude Bernard Lyon 1, Ecole Centrale de Lyon, CNRS, Ampère, Villeurbanne, France
[3] Institut National de la Recherche Scientifique (INRS), centre Energie, Matériaux, Télécommunications, Varennes, Québec, Canada
[4] Université Côte d'Azur, CNRS, CRHEA, Valbonne, France

Abstract text: Gallium Nitride (GaN) has gained prominence in semiconductor applications due to its wide band gap, high electron velocity, excellent thermal conductivity, and a high critical electric field, positioning it as ideal material for high-power, high-frequency, and high-temperature applications. Vertical GaN transistors, particularly in power electronics, offer high breakdown voltage and low on-state resistance but face challenges such as self-heating, which can degrade performance. Accurate measurement of channel temperature is crucial for packaging design and thermal management, yet self-heating in vertical GaN transistors (FinFET and NWFET) remains unexplored. To explore this challenge, Raman spectroscopy is employed to quantify the impact of temperature and doping on E_2(high) and A_1(LO) Raman mode frequencies. The Raman spectra of Si-doped GaN homo-epitaxial layers exhibit distinct E2(high) and A_1(LO) modes (Figure 1), with doping significantly affecting the latter. The A_1(LO) mode undergoes a blue shift and broadening due to phonon-plasmon coupling above $N_D=4.7\times10^{17}$ cm^{-3} (Figure 2), while the E_2(high) mode redshifts consistently, indicating possible induced stress effects. Temperature-dependent Raman spectra reveal expected shifts, with the E_2(high) mode redshifting. The A_1(LO) mode exhibits stronger shifts $\Delta\omega$=6.9 to 8.7 cm^{-1} and broadening from $\Delta\Gamma$=4.7 to 35.4 cm^{-1} for $N_D=1\times10^{15}$ cm^{-3} to $N_D=1.8\times10^{18}$ cm^{-3} (Figure 3). A_1(LO) fitting parameters show a linear correlation with doping, enabling temperature-doping estimation. The evolution of A_1(LO) vs. E_2(high) mode frequency reveals that A_1(LO) is nearly twice as temperature-sensitive as E_2(high) up to $N_D=4.7\times10^{17}$ cm^{-3}, while at $N_D=1.8\times10^{18}$ cm^{-3}, both modes provide equivalent temperature accuracy (Figure 4). A 3D representation (Figure 5) showing the (ω_{A1}, N_D, T_L) enables temperature and doping estimation. Fano fitting of the A_1(LO) mode reveals linewidth variations from $\Delta\Gamma_{Fano}$= 15 cm^{-1} and Fano parameter with temperature (Figure 6, 7), serving as an indicator of Fermi level evolution in heavily doped GaN.

PC-Mon-P47* - GaN advancing biofilm dynamics through surface engineering

2. Physics and characterization
Eon-Bee Lee[1]
Hyeon-Ju Lee[1], Jeong-Gil Kim[2]
[1] Department of Aquatic Life Medicine, Pukyong National University, Busan 48513, Republic of Korea
[2] Department of Semiconductor, Dong-A University, Busan 49315, Republic of Korea

Abstract text: Gallium nitride (GaN) has long been valued for its superior electrical and optical properties, playing a crucial role in high-power electronics and optoelectronic devices. Recent advancements in GaN surface engineering have expanded its potential applications beyond traditional semiconductor uses, particularly in interfacial science and biointerface engineering. Understanding the interaction between engineered GaN surfaces and biological systems is essential for developing functional materials in medical and industrial applications. This study explores the role of GaN surface modifications in biofilm dynamics, aiming to elucidate how engineered interfaces influence microbial adhesion and antibiotic susceptibility.
GaN underwent plasma treatment, nanostructuring, and chemical functionalization to investigate their effects on biofilm formation. *Pseudomonas aeruginosa* (*P. aeruginosa)* and *Staphylococcus aureus* (*S. aureus)*were cultured on these surfaces, and biofilm formation was quantified via crystal violet staining and optical density measurements at 550 nm (OD550). Ga^{3+} ion release was analyzed using inductively coupled plasma mass spectrometry (ICP-MS), while minimum inhibitory concentration (MIC) and biofilm eradication assays were performed to assess antimicrobial effects. Surface modifications significantly influenced bacterial adhesion and biofilm formation. Plasma-treated GaN surfaces exhibited a 42% reduction in biofilm biomass, while nanostructured GaN further decreased adhesion by 63% compared to untreated GaN ($p < 0.01$). ICP-MS analysis showed controlled Ga^{3+} ion release, peaking at 2.1 μg/mL at 72 hours, which correlated with observed biofilm inhibition. MIC assays indicated a 1.8-fold increase in antibiotic susceptibility for *P. aeruginosa* biofilms grown on GaN surfaces, suggesting surface interactions modulate bacterial resistance. Furthermore, biofilm eradication assays showed a 56% reduction in viable biofilm cells upon enrofloxacin treatment on modified GaN surfaces, highlighting enhanced antimicrobial effects. These findings reveal that GaN surface engineering can effectively modulate biofilm dynamics, offering a novel approach to microbial surface interactions. The tunable properties of GaN interfaces present new opportunities for antimicrobial coatings, biomedical implants, and bioelectronic applications.

PC-Mon-P48 - Impact of Minority Carrier Injection on the Annealing Behavior of Nitrogen Interstitials in Homoepitaxial n-type GaN

2. Physics and characterization

Meguru Endo[1]
Jun Suda[1], Masahiro Horita[1]
[1] Nagoya University

Abstract text: Understanding point defects (PDs) in GaN is essential for realizing a superior device since various PDs may be introduced through device fabrication. However, most of the origins of deep levels (DLs) in GaN are still unclear.

The intentional introduction of PDs by electron beam (EB) irradiation is an effective method for investigating the DLs that originate from intrinsic defects. We have reported that 137-401 keV EB-irradiation to n-type GaN displaces nitrogen (N) atoms selectively, and nitrogen interstitial (N_I) forms electron trap, EE2 (E_C −1.1 eV), in n-type GaN. Our previous study also revealed a migration barrier of N_I in n-type GaN of 2.0 eV for −1 charge and 2.3 eV for neutral or + charge, which were obtained by evaluation of the thermal annealing behavior of EE2. In this study, we discovered a unique phenomenon in p-n junction diodes (PNDs) where injecting minority carriers, namely holes, into the n-type GaN results in a decrease in the concentration of EE2. Furthermore, we investigated the annealing behavior of EE2 by minority carrier injection and obtained the activation energy (E_a) of annealing rates using p-n junction diodes.

The GaN p^+-n^- diode samples with mesa structure were used. The EB irradiation was performed at the energy of 137 keV after the ohmic contact formation of PNDs. Isothermal capacitance transient spectroscopy (ICTS) measurements were performed to investigate the annealing behavior of EE2. From ICTS measurements, the concentration of EE2 (N_{EE2}) was about half after minority carrier injection for 50 s with a current density of 20 Acm^{-2} at 300 K. This annealing was not caused by irradiation of light generated by electron-hole recombination at the p-n junction interface since there was no change in the N_{EE2} before and after irradiation of an optical wavelength of 391 nm for 30 min. We also analyzed an annealing rate from the injection time dependence of N_{EE2}. From the temperature dependence of the annealing rate of EE2, the E_a of 0.31 eV was determined. This value was significantly smaller than the migration barrier of 2.0 eV. These results indicated that the annealing behavior of EE2 was caused by electron-hole recombination at EE2, a so-called recombination-enhanced defect reaction.

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PC-Mon-P49* - Investigation of Electrical Properties and Ohmic Contact Behaviour in Cubic Gallium Nitride with Different Silicon Doping Levels

2. Physics and characterization

Surender Subburaj[1]
Menno J. Kappers[2], Rachel A. Oliver[2], David J. Wallis[1]
[1] Centre for High Frequency Engineering, Cardiff University, Cardiff, United Kingdom.
[2] Department of Materials Science & Metallurgy, University of Cambridge, Cambridge, United Kingdom.

Abstract text: Cubic gallium nitride (GaN) is emerging as a promising alternative to hexagonal GaN due to the absence of internal electric fields along the [001] direction and its narrower bandgap, which enhances its suitability for high-performance light-emitting diodes (LEDs) at longer wavelengths [1]. This study investigates the electrical properties of ohmic contacts on cubic GaN epilayers grown on 3C-SiC/Si(001) substrates off-cut by 4 degrees towards [110], with different nominal Silicon doping concentrations of 1×10^{17} cm^{-3}, 1×10^{18} cm^{-3}, and 2×10^{19} cm^{-3}. A conventional Ti/Al/Ti/Au metal stack, optimized for hexagonal GaN and similar to that given in [2], was applied to cubic GaN, and the contact resistance was evaluated using the Transmission Line Model (TLM).

At the highest doping level, a contact resistance (Rc) of 0.280 Ω·mm was achieved, demonstrating values better than hexagonal GaN (Rc = 0.354 Ω·mm). Additionally, the extracted specific contact resistivity (ρc) and transfer length (LT) were found to strongly depend on doping concentration. It has also been seen that the stacking fault (SF) density in cubic-GaN layers can be very different along orthogonal crystal directions relative to the substrate off-cut [3]. An attempt was made to assess the impact of SFs on electrical transport by using both perpendicular (V-TLM) and parallel (H-TLM) TLM configurations relative to the miscut direction. For the highest conductivity sample, differences in the sheet resistance can be measured along the orthogonal directions which may be correlated with differences in stacking fault density along the current path.

These findings confirm that standard ohmic contact processes used for hexagonal GaN can be effectively adapted to cubic GaN to deliver a viable device technology.

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PC-Mon-P50* - High n-type Doping of GaN by Germanium Ion Implantation

2. Physics and characterization

Kacper Sierakowski[1]
Leszek Konczewicz[2], Lutz Kirste[3], Karol Kawka[2], Robert Czarnecki[2], Marcin Turek[4], Tomasz Sochacki[2], Michal Bockowski[2]
[1] Department of Material Science and Engineering, North Carolina State University, Raleigh, NC, USA
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland
[3] Fraunhofer Institute for Applied Solid State Physics IAF, Freiburg im Briesgau, Germany
[4] Maria Skłodowska-Curie University, Lublin, Poland

Abstract text: The n-type doping of gallium nitride (GaN) is one of the most crucial technologies for GaN-based semiconductor devices. The most common donor dopant in GaN is silicon (Si). It is the dopant of choice, as it can be introduced either during crystallization or ion-implantation (I/I). However, Si has a limitation in the form of "compensation knee", a phenomenon where adding more Si past a certain critical concentration results in the decrease of free carrier concentration. In some applications such as under-contact layers in power devices strongly conductive n-type regions are required. For these applications free charge carrier concentration should reach 10^{20} cm^{-3} order of magnitude. An alternative donor dopant for GaN is germanium (Ge). In Ge-doped GaN free electron concentration is strictly proportional to the concentration of incorporated Ge without an observable compensation effect. Unfortunately, growth of bulk GaN:Ge is challenging owing to the strain emerging during growth which leads to cracking of the crystal.

In this work, we present the structural and electrical properties of GaN:Ge obtained by ion implantation of germanium into GaN layers grown by Halide Vapour Phase Epitaxy (HVPE) and Metalorganic Vopor Phase Epitaxy (MOVPE). To achieve box-shaped Ge profiles multi-step implantation process was performed and the target doping level was from 5×10^{18} to 10^{20} cm^{-3}. After the implantation, the samples were annealed using Ultra-High-Pressure Annealing (UHPA) technology for Ge activation and removal of I/I-induced damage of crystal structure. Diffusion of Ge was analyzed using secondary ion mass spectrometry. The structural quality of both epi-layers and implanted layers were analyzed by X-ray Diffraction. Electrical parameters of obtained layers were examined by Hall effect measurements. The successful partial activation (25-50%) of germanium in I/I samples and the annealing time dependance is presented. Good recovery of crystallographic quality after UHPA is confirmed. The diffusion of Ge was not observed during annealing process. Even without full activation of the introduced Ge, the achieved free carrier concentrations are high (reaching 5×10^{19} cm^{-3}), combining this with good structural recovery and lack of diffusion makes Ge ion implantation a suitable way for selective area n-type doping.

OD-Mon-P1 - Impact of quantum well number on the internal quantum efficiency in 233 nm Aluminium Gallium Nitride light emitting diodes: a simulation study

3. Optical devices

Friedhard Römer[1]
Ibrahim Marouf[1], Marcel Schilling[2], Jan Ruschel[3], Hyun Kyong Cho[3], Jens Rass[3], Sven Einfeldt[3], Jakob Höpfner[2], Martin Guttmann[4], Tim Wernicke[2], Michael Kneissl[4], **Bernd Witzigmann**[1]
[1] Friedrich-Alexander-Universität Erlangen-Nürnberg, Institute of Optoelectronics, Erlangen, Germany
[2] Technische Universität Berlin, Institute of Solid State Physics, Berlin, Germany
[3] Ferdinand-Braun-Institut (FBH), Berlin, Germany
[4] Technische Universität Berlin, Institute of Solid State Physics, Berlin, Germany; Ferdinand-Braun-Institut (FBH), Berlin, Germany

Abstract text: Aluminium gallium nitride (AlGaN) deep ultraviolet light (DUV) emitting diodes (LED) present an enabling technology in many fields, including environmental and medical applications. DUV LEDs emitting near 265 nm wavelength are maturing, but the design becomes increasingly challenging with decreasing emission wavelength. In addition to low hole injection efficiency and high absorption the carrier confinement in quantum wells for emission in the far-UVC < 240 nm is limited because the barrier band offset decreases with decreasing emission wavelength. The reduction of the barrier height limits the radiative recombination and promotes carrier escape from the active region. An obvious solution is to increase the number of quantum wells. In this context we have investigated the effect of the quantum well number on the carrier confinement and distribution in a 233 nm AlGaN LED with up to 30 multi-quantum wells (MQW) by numerical modelling. Simulations are targeted to the carrier injection efficiency as well as the distribution of the luminescence in the MQW stack. The simulations have been performed with a multi scale carrier transport solver including a microscopic luminescence model. Alloy disorder leading to inhomogeneous broadening (IHB) is considered. The carrier transport parameters have been calibrated with the spectral data of a mixed quantum well AlGaN LED and a 265 nm AlGaN LED. The simulation results show good agreement with experimental data of the 233 nm MQW series. The carrier transport modelling of the multi quantum well 233 nm LED shows that the carrier injection efficiency increases with the number of quantum wells finally saturating. Since the single well radiative recombination efficiency depends on the captured carrier density it also changes with the number of quantum wells. Even for 30 quantum wells the electron leakage does not vanish because of the limited hole injection efficiency. The low hole mobility does not significantly impede the hole distribution in the active region and thus the luminescence re-distribution, though. We also demonstrate that the optimum number of quantum wells depends on the targeted current density and discuss the impact of reabsorption. The simulations suggest that the number of quantum wells is a critical parameter in the design of far-UVC LEDs.

OD-Mon-P2 - Effect of light polarization on light extraction efficiency of deep-ultraviolet light-emitting diodes

3. Optical devices

Kirill A. Bulashevich[1]
Olga S. Soboleva[1], Mikhail E. Rudinsky[1]
[1] Semiconductor Technology Research d.o.o. Beograd, Belgrade, the Republic of Serbia

Abstract text: Light extraction efficiency (LEE) of deep-ultraviolet light-emitting diodes (deep-UV LEDs) suffers from many factors, such as poor reflectivity of metallic contacts in deep-UV spectral range, light absorption in p-GaN contact layer, lack of UV-stable encapsulants, and so on [1]. It is known that TE photons are emitted uniformly over the solid angle, while angular distribution of TM photons depends on the AlGaN material composition, strain, and thickness of the quantum well (QW). This study is aimed in understanding effect of this anisotropy on LEE.

First, k·p model with wavevector-dependent interband matrix element was used to calculate the angular emission pattern of TM photons [2]. Within some reasonable simplifications, the angular dependence of TM emission pattern can be analytically expressed through the degree of polarization (DoP) for light emitted in lateral direction.

Next, ray tracing simulations [2] with varied DoP were performed for 280 nm emission for two chips: (i) commercial-like large planar flip-chip (950x950 μm^2) and (ii) square micro-pyramid flip-chip with SiO_2/n-metal reflector on top of the pyramid sidewalls with angle of 55° to lateral direction (30x30 μm^2). Three different metallic n-contact were compared (Ag-, Rh-, and Al-based), while the p-contact was always Au-based. Absorption in p-GaN layer was neglected assuming a conductive p-AlGaN contact layer.

For large chip, the LEE increases with DoP from ~11% at DoP=-1 (mostly lateral emission) to ~17% at DoP=1 (mostly vertical emission), with a weak dependence on the n-contact metal. It should be noticed that LEE variation with DoP is related not only to change of the angular emission pattern, but also to a lower reflection of TM photons at the metallic contacts compared to TE photons. For micro-pyramid chip, the overall LEE value is higher and its dependence on the n-metal is stronger. Surprisingly, the LEE of micro-pyramid chip may increase or decrease with DoP depending on the SiO_2 thickness (30 nm or 100 nm) and n-contact metal, which is a combined effect of sloped sidewalls and light interference in SiO_2/metal reflector. Further detailed analysis of DoP effect on LEE will be presented, including chip size, effect of sloped sidewalls, and design of SiO_2/metal reflector.

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OD-Mon-P3* - Advancing UV-C LED performance: a comparative appraisal of p-contact strategies in AlGaN devices

3. Optical devices

Francesco Mercinelli[1]
Lorenzo Miri[1], Alberto Tibaldi[1], Michele Goano[1], Francesco Bertazzi[1]
[1] Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Torino, Italy

Abstract text: The optimization of UV-C LEDs requires overcoming challenges associated with electrical contacts and light extraction. In this work, we compare the efficiency of three solutions for contact layers in AlGaN-based UV-C LEDs through a quantum-corrected drift-diffusion method: A Mg-doped *p*-GaN contact, a polarization-doped graded AlGaN contact (GC), and tunnel junctions (TJ).

A *p*-GaN layer is traditionally used in AlGaN-based LEDs to implement an ohmic contact due to the poor Mg doping ionization of high-Al-concentration nitrides. However, it suffers from high absorption of UV-C light, which limits the light extraction efficiency (LEE).

As a possible alternative, polarization doping exploits polarization charges in graded AlGaN alloys to achieve high hole concentrations even for large aluminum molar fractions. This approach provides a transparent alternative for improving contact characteristics without the need for extrinsic dopants, and avoiding light losses.

Another solution explored is based on tunnel junctions. Aiming towards a rigorous description of band-to-band tunneling, the quantum-corrected drift-diffusion is augmented with a multi-band non-equilibrium Green's function (NEGF) method. Tunnel junctions have the potential to improve light extraction efficiency (LEE) by providing a good ohmic contact with high band-gap n-type AlGaN and a high-reflectivity metal contact.

To perform a comparative appraisal of these solutions, we present the internal quantum efficiency (IQE), the light extraction efficiency (LEE), and the wall plug efficiency (WPE) for each device. The results indicate that while all three devices achieve a similar maximum IQE of 57%, the voltage at which this maximum is achieved differs. The *p*-GaN and the GC devices reach peak IQE at lower voltages compared to the TJ, due to the voltage penalty. The GC enhances light extraction due to reduced absorption of the contact layer yielding a LEE of 14% and an EQE of 8%, while the TJ provides the highest LEE (19%) and EQE (10%) due to the higher reflectivity of the contact metal. The WPE for the *p*-GaN contact is 5%, while the GC and TJ contacts show improvements, achieving WPEs of 6% and 9%, respectively. The TJ shows a lower improvement due to the increased electrical power needed.

These findings highlight the importance of optimizing contact layers to improve the efficiency of UV-C LEDs.

OD-Mon-P4 - Realizing a High External Quantum Efficiency of 0.44% in 232 nm AlGaN-based far-UVC LED by Suppressing Relaxation in n-AlGaN Layer Via Homoepitaxy

3. Optical devices

Muhammad Ajmal Khan[1]
Hiromitsu Sakai[2], M. Nawaz Sharif[1], Arata Sasaki[3], Amina Yasin[1], Yuya Nagata[4], Yukio Kashima[1], Mitsuhiro Muta[5], Yasushi Iwaisako[5], Hiroyuki Yaguchi[6], Hideki Hirayama[1]
[1] RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[2] Shin-Etsu Chemical Co., Ltd. Japan
[3] RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan/Saitama University, Saitama 338-8570, Japan
[4] RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan /Saitama University, Saitama 338-8570, Japan
[5] Nippon Tungsten Co., Ltd., Minoshima 1-2-8, Hakata-ku, Fukuoka-shi 812-0017, Japan
[6] Saitama University, Saitama 338-8570, Japan

Abstract text: An AlN bulk substrate is preferred for the epitaxial growth of AlGaN-based far-UVC LEDs due to its low threading dislocations (TDs), however, it is very expensive (800 USD/2-inch wafer) [1]. Additionally, a relatively less expensive and time-consuming method known as double-growth and double high-temperature annealing (DGA) has been proposed by several researchers for the epitaxial growth of far-UVC LEDs [2,3]. Using a 2 μm-thick AlN template layer on a re-grown AlN layer, along with a DGA AlN template, resulted in an improved external quantum efficiency (EQE) of 0.24-0.70% for (230-233nm)-band far-UVC LEDs [2,3]. In our laboratory, we enhanced the crystal quality of a low-cost AlN template grown on inexpensive c-(0001)-plane sapphire substrates (10 USD/2-inch wafer) by employing an ammonia (NH_3) pulsed-flow multilayer (ML) growth [4]. However, we encountered an issue of relaxation ratio ≥ 37% in the n-AlGaN electron injection layer (EIL) of LED using ud-AlGaN heteroepitaxy directly on a 4 μm-thick AlN layer on c-plane sapphire. The reported EQE was 0.32%, with a light power output of 1.8 mW for a 228 nm far-UVC LED [4]. The low performance observed may be attributed to the high TDs and high relaxation ratio of 37% in n-AlGaN EIL beneath the multiple quantum wells (MQWs) using ud-AlGaN heteroepitaxy (transverse magnetic (TM)-mod ≥ transverse electric (TE)-mode). A low relaxation ratio is essential for suppressing TM-mode emission and enhancing TE-mode emission due to the piezoelectric field. In previous cases involving blue LEDs fabricated on GaN templates, the light output power (Po) was significantly enhanced by introducing a regrowth of the GaN homoepitaxial layer. In this work, we introduced a new method of AlN homoepitaxy instead of heteroepitaxy (ud-AlGaN) on MOVPE-grown AlN templates, aided by a special thermal cleaning treatment before the growth of LED. As a result, the relaxation ratio in the n-AlGaN EIL beneath the MQWs substantially decreased from 37% [4] to 22%. Consequently, the EQE in the 231nm far-UVC LED improved from 0.3% to 0.44% on the wafer (this work) under continuous wave/pulse operation. The improved light power output reached 3.2 mW on the wafer under pulse operation at room temperature. The operating voltage was also reduced. An EQE of more than 0.8% is expected If the flip-chip and lens are mounted on the improved far-UVC LED.

OD-Mon-P5* - High Power AlGaN-Based Deep Ultraviolet Light Emitting Diodes with Chip-Scale Liquid Cup

3. Optical devices

Linbo Hao[1]
Yanan Guo[1], Xue-Jiao Sun[1], Shen Wang[2], Xiaojun Jia[2], Junxi Wang[1], Jinmin Li[1], Jianchang Yan[1], **Naixin Liu**[1]
[1] Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
[2] State Key Laboratory of Quantum Optics Technologies and Devices, Shanxi University, Taiyuan, Shanxi 030006, China

Abstract text: AlGaN-based deep ultraviolet light-emitting diodes (DUV LEDs) have garnered attention for applications in water sterilization, air purification, and biomedical sensing. However, the highest wall-plug efficiency (WPE) of high-power DUV LEDs at 350 mA, reported as 8.25%, remains low compared to blue LEDs. With the advancement of AlGaN growth technology, the low light extraction efficiency (LEE) has emerged as a crucial factor influencing the performance of DUV LEDs.

The low LEE is caused by total internal reflection (TIR), which arises from the high refractive index contrast between AlGaN and air. Using optical materials with a higher refractive index can reduce TIR, such as fluororesin structures, and silicone oil cavities. Among these, fluorinated materials demonstrate superior reliability under prolonged UV exposure due to the higher energy of C-F bonds. Additionally, inclined sidewall holds significant potential in enhancing the LEE of Micro-LEDs, because the emitted light can easily propagate towards inclined sidewall. However, for DUV LEDs with large chip sizes, most of the emitted light tends to propagate into sapphire and is hard to reach the relatively small inclined sidewalls. Therefore, it is important to explore the novel large-area inclined sidewall structure for enhancing the performance of high-power DUV LEDs.

In this work, a fluorine-based oily liquid is employed to form a self-assembled liquid cup with a large area inclined sidewall encompassing the entire chip. This self-assembled phenomenon is attributed to the equilibrium among adhesion, surface tension, support force and gravity within the entire system, which includes the chip, quartz, and the oily liquid. Experimental and simulation results demonstrate that the liquid cup can efficiently enhance the LEE by enlarging the light escape cone, supporting an additional out-light area and utilizing scattering effect from its large-area inclined sidewall. Moreover, the presence of a large inclined sidewall in the liquid cup effectively tunes light towards the vertical direction.

The DUV LED with the liquid cup achieves a light output power of 202 mW and a WPE of 10.74% at 350 mA. The peak WPE reaches 13.24% at 5 mA. Compared to conventional DUV LEDs, the WPE is enhanced by 64.9%. Our method paves the way for advancing the development of DUV LEDs.

OD-Mon-P6* - Numerical simulations of the capacitance-voltage characteristics of AlGaN-based far-UVC LEDs

3. Optical devices

Nicola Roccato[1]
Francesco Piva[1], Matteo Buffolo[1], Carlo De Santi[1], Nicola Trivellin[2], Marcel Schilling[3], Anton Muhin[3], Jakob Höpfner[3], Martin Guttmann[4], Tim Wernicke[3], Michael Kneissl[5], Gaudenzio Meneghesso[1], Enrico Zanoni[1], Matteo Meneghini[6]
[1] Department of Information Engineering, University of Padova, via Gradenigo 6/B, 35131 Padova, Italy
[2] Department of Information Engineering, University of Padova, via Gradenigo 6/B, 35131 Padova, Italy, Department of Industrial Engineering, University of Padova, via Gradenigo 6/A, 35131 Padova, Italy
[3] Technische Universität Berlin, Insitute of Solid State Physics, Hardenbergstr. 36, 10623 Berlin, Germany
[4] Ferdinand-Braun-Institut, Leibnizinstitut für Höchstfrequenztechnik gGmbH, Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany
[5] Technische Universität Berlin, Insitute of Solid State Physics, Hardenbergstr. 36, 10623 Berlin, Germany,Ferdinand-Braun-Institut, Leibnizinstitut für Höchstfrequenztechnik gGmbH, Gustav-Kirchhoff-Str
[6] Department of Information Engineering, University of Padova, via Gradenigo 6/B, 35131 Padova, Italy, Department of Physics and Astronomy, University of Padova, via Marzolo 8, 35131 Padova, Italy

Abstract text: Capacitance-voltage characterization is widely used for the extraction of charge profiles in pn abrupt junctions; however, this technique has not been optimized in presence of complex device structures, such as AlGaN-based heterostructures and quantum-well devices. To fill this gap, we defined a modeling approach for the capacitance-voltage (C-V) curves of multi-quantum well UV-C LEDs. The active region of the devices consists of two QWs emitting at 233 nm and one emitting at 250 nm. The LED structure was reproduced by Sentaurus TCAD in order to compare the simulated capacitance characteristic and the apparent charge profile (ACP) with the experimental ones.

First approaches (considering an ideal structure) do not show good agreement with the experimental data; for this reason, a tuning based on realistic device parameters was implemented, including:

1. the impact of interface defects and polarization charges, which modify the voltage required to displace the edge of the SCR towards the n-side, effectively shifting the apparent charge profile at lower voltages;
2. the Schottky nature of the p-contact, which induces the formation of a depletion region at the metal/semiconductor junction, adding another bias-dependent capacitance in series to the junction capacitance.
3. The impact of carrier injection efficiency that determines the carrier density especially in the first QW close to the n-side. To this aim, a direct tunneling model, based on the WKB approximation, was implemented in the last 10 nm of the first barrier adjacent to the QW.

The model, appropriately calibrated by accounting for the non-idealities described above, allows to achieve an accurate reproduction of the CV characteristic and ACP of the investigated device. The results presented in this paper provide relevant information for UV-C LED characterization and modeling.

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OD-Mon-P7* - Design and Fabrication of Group III Nitride Based Ultraviolet Light Emitting Diode

3. Optical devices

ARNAB MONDAL[1]
APURBA LAHA[1]
[1] INDIAN INSTITUTE OF TECHNOLOGY BOMBAY, IIT BOMBAY, MUMBAI,INDIA

Abstract text: Gallium Nitride (GaN)-based ultraviolet light-emitting diodes (UV-LEDs) have been employed for numerous optoelectronic applications and have become an integral part of our lives today [1].
The proposed research is directed towards designing a UV-LED tuned for a specific wavelength range between 278-282 nm, with very high intensity. This range is selected for its superior germicidal effectiveness and minimal material absorption losses. To achieve this objective, we have designed an AlGaN-based multi-quantum well LED heterostructure and simulated the required heterostructure using TCAD SILVACO software. Simulation results reveal that the proposed device has a peak emission at 281 nm with a power spectral density of 13 W/cm-eV at an operating voltage of 5 V. Simulation results also show that the electron and hole wavefunction overlap value ($\Gamma_{e\text{-}hh}$) in the last pair of the quantum well along the growth direction is 92.45%. The ultimate aim of our work is to mitigate the polarization-induced in-built electric field in the quantum well (QW) and thereby reduce the Quantum Confined Stark Effect (QCSE). This phenomenon reduces the electric field intensity inside the quantum well and flattens the energy band of the QW.
Following the theoretical analysis, we proceed with fabricating an optimized LED structure to validate our findings experimentally. In order to fabricate the LED with an optimized heterostructure, we start by implementing a metal-semiconductor (MS) contact for the electron injection layer. It is really a great challenge to realize low-resistance MS ohmic contact on an Al-rich n-type AlGaN layer. To address this challenge, we deposited a novel Nb/Al/Ni/Au metallic scheme on n-$Al_{0.55}Ga_{0.45}N$ substrate and annealed it at 720°C for 3 minutes in an ultra-high purity nitrogen atmosphere. Niobium is used for its low work function and high conductivity, enabling efficient electron injection into Al-rich n-AlGaN. From the ohmic I-V curves of different devices, the contact resistance and specific contact resistivity of MS contact are calculated to be 3.66 Ω and 5.65×10^{-5} Ω-cm^2 respectively. Hence, these observations prompt us to claim that our designed device with its high UV intensity exhibits strong potential for the disinfection of microorganisms and bacteria in drinking water.

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OD-Mon-P8* - Unveiling and eliminating the parasitic hole loss in AlGaN-based deep-ultraviolet light-emitting diodes

3. Optical devices

Chengzhi Ji[1]
Fujun Xu[1], Jiaming Wang[1], Jing Lang[1], Bo Shen[1]
[1] State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China

Abstract text: AlGaN-based deep-ultraviolet light-emitting diodes (DUV-LEDs) have attracted much attention owing to their extensive applications, including sterilization, non-line-of-sight communication, and maskless photolithography. However, the commercial application is severely restricted by the low wall-plug efficiency (WPE). As the foundation of device operation, the carrier injection efficiency (CIE) is vital in determining the WPE. Hindered by the extremely inefficient p-doping of Al-rich AlGaN as well as much lower mobility of holes, the carrier injection is generally asymmetric in DUV-LEDs, i.e. there are excess electrons in the active region. These electrons can easily overshoot and leak into the p-region, resulting in the hole loss by unexpected recombination.

In this work, the parasitic hole loss owing to the electron accumulation at the active region/EBL interface is experimentally unveiled in AlGaN-based DUV-LEDs. It is demonstrated that the loss arises mainly through the non-radiative recombination process, making it unnoticeable under normal operating conditions, e.g. at room temperature. A strategy featuring the last quantum barrier free in the MQW active region is accordingly proposed to propel the electron accumulation into the last quantum well [Fig. 1(a-b)], which greatly promotes the CIE. As a consequence, holes can be effectively injected into the wells without parasitic loss, as shown in Fig. 1(c-d), where efficient radiative recombination for DUV emission occurs as hoped. The light output power (LOP) in 277 nm DUV-LEDs reaches 51.7 mW (at 100 mA) after encapsulation, ~23% higher than that retaining the last quantum barrier. Meanwhile a maximum WPE of 9.98% is realized [Fig. 2(a-b)], one of the highest values reported to date. The strategy in this study is compatible with the present commercial DUV-LED epitaxial structure, enabling it to promote further development of this field.

OD-Mon-P9* - Selective removal of thin Al-rich AlGaN films by photo-assisted electrochemical etching

3. Optical devices

Phuc T. Nguyen[1]
Artem Shushanian[1], Ryan Page[1], Verena Montag[2], Tim Wernicke[2], Michael Kneissl[2], Joachim Ciers[1], Åsa Haglund[1]
[1] Department of Microtechnology and Nanoscience, Chalmers University of Technology, 41296 Gothenburg, Sweden
[2] Institute of Solid-State Physics, Technical University of Berlin, 10623 Berlin, Germany

Abstract text: Substrate lift-off for UVC (200–280 nm) emitters is crucial for realizing novel devices such as VCSELs and thin-film flip-chip LEDs. Electrochemical etching (ECE) of a sacrificial $Al_xGa_{1-x}N$ layer has proven to be excellently suited to lift off devices with high precision and selectivity. However, conventional ECE struggles to etch layers with high Al mole fraction and, in our experience, only leads to porosification and not complete etching even at high voltages. High applied voltages also increase the risk to porosify other doped device layers. Here, we present a strategy to completely etch Al-rich layers by adding photoexcitation of the sacrificial layer. By choosing the right excitation wavelength for photo-assisted ECE (PECE) we were able to achieve complete etching of sacrificial layers with up to 65% Al using moderate voltages of 15 V for the first time.

The investigated heterostructures consist of an AlGaN current spreading layer, a sacrificial multi-layer 5x(5 nm $Al_xGa_{1-x}N$/5 nm $Al_yGa_{1-y}N$), (x/y [%/%]) = (38/48, 45/55 and 55/65) and an $Al_{0.76}Ga_{0.24}N$ membrane which is to be released. We etched these samples in a two-electrode system in 3 mM HNO_3, illuminating the samples through the substrate side. Higher optical power densities (0–23 mW/cm²) increase the lateral etch rate. However, we always observe the porosification of the current spreading layer for all illumination intensities whereas the under-etched membranes do not show signs of etching. We also tested different PECE illumination wavelengths on a (55/65) sacrificial layer. Illumination at 275 nm leads mainly to porosification. However, at 265 nm, we obtain complete removal of sacrificial layers at 15 V, due to a higher absorption in the sacrificial layer at the shorter wavelength. The exposed N-polar side of the membrane has an RMS roughness of 5.6 nm (38/48), 5.8 nm (45/55), and 7.4 nm (55/65). Thus, an Al-richer sacrificial layer leads to a slightly rougher etched surface. These roughnesses are smoother than those obtained by laser lift-off and high-pressurized water, and the PECE-based lift-off also results in a precise thickness control of the lifted-off membrane. This demonstration of selective etching of Al-rich layers with decently smooth surfaces opens a new path for thin-film flip-chip UVC LEDs, UVC VCSELs, and photonic integration of UVC emitters on any platform.

OD-Mon-P10* - A novel band broadening model for stimulated emission in Aluminium Gallium Nitride quantum wells with alloy fluctuations

3. Optical devices

Sebastian Kölle[1]
Friedhard Römer[1], Bernd Witzigmann[1]
[1] Institute of Optoelectronics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

Abstract text: The large band gap of Aluminium Gallium Nitride (AlGaN) allows realization of ultraviolet semiconductor lasers with a broad field of prospective applications.

Strong alloy disorder in AlGaN leads to localized electronic band states, each with their own set of transitions contributing to radiative recombination. This causes inhomogeneous broadening (IHB) of the laser's gain spectrum. But while the states in disordered semiconductors can be calculated with atomistic models [1], the resulting glut of data needs to be condensed for gain calculation. Reconstructing a dispersion relation [2] shows these localized states to form a Gaussian distribution around the fluctuation-free conduction $E_n(k)$ and valence $E_m(k)$ subbands [3].

Here, a gain calculation based on broadened subband dispersions is presented. We calculate the eigenstates E_n, E_m through a self-consistent Schrödinger-Poisson iteration on the k·p Hamiltonian. Due to the high carrier density required to achieve lasing, we include Coulomb scattering in these states by a 2nd order Born approximation to account for homogeneous broadening (HB) of the spectrum.

The Gaussian broadening of each subband is locally correlated due to seeing the same local composition, with an overall variation ε to the bandgap E_g. A perturbation approach on the Hamiltonian shows that the bands shift to $E_n(k)+2/3\varepsilon$ and $E_m(k)-1/3\varepsilon$. This matches experimental results [4].

Sweeping the Gaussian distribution of ε leads to broadened bands. These, alongside the scattering calculations, are then inserted into our gain model to derive the gain spectrum with both IHB and HB.

The resulting gain spectra and density of states are consistent with [1] and can match experimental spectra in width and Urbach tail. We find IHB to cause changes relevant to laser design such as lower transparency density and reduced peak gain at higher densities.

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OD-Mon-P11* - Simultaneous edge and surface stimulated emissions from optically pumped AlGaN-based deep ultraviolet laser bars

3. Optical devices

Yanan Guo[1]
Han Wu[1], Ruijie Zhang[1], Zhibin Liu[1], Jianchang Yan[1], Junxi Wang[1]
[1] Research and Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

Abstract text: AlGaN-based deep ultraviolet laser diodes possess many advantages over traditional UV solid and gas lasers, and promise to be applied in the fields of disinfection, biochemical detection, material processing and solar-blind communication. The optically pumped stimulated emission performance of edge-emitting laser bars is frequently used as a preset study for the development of a practical electrically pumped laser. The threshold optical power density and the linewidth after the threshold can reveal information regarding the crystalline quality, carrier confinement capability and the optical confinement factor of the active region. However, the optical pumping measurement requires elaborated preparation of laser bars, and the results are susceptible to the facet quality after cleavage or the mesa etch.

In this work, we found that the surface optical pumping would trigger a surface-stimulated emission (SSE) from unprocessed AlGaN-based DUV laser wafers at a sufficiently high excitation power density, which can be used to predict the performance of lasers by simply assessing the surface lasing characteristics. Such SSE was even simultaneously observed with edge-stimulated emission (ESE) in laser bars. The onset threshold and the linewidth of SSE are independent of the cavity length of laser bars and similar to those obtained in a surface emitting measurement setup for unprocessed laser wafers. The SSE is deduced to stem from the vertical optical resonance within the epilayers. Furthermore, as the growth temperature of the n-AlGaN cladding layer increased from 1035 to 1115 ℃, the onset lasing threshold and the linewidth of stabilized SSE in the laser bar with 1-mm cavity length respectively reduced from 154 kW/cm^2 to 109 kW/cm^2 and from 1.38 nm to 1.28 nm. Meanwhile, the lasing threshold and linewidth of ESE in the same laser bar reduced from 159 kW/cm^2 to 85 kW/cm^2 and from 1.15 nm to 0.87 nm, respectively. The improved lasing performance is attributed to the lowered internal loss in the n-AlGaN cladding layer. Despite the different resonance directions of SSE and ESE, the positive correlation between SSE and ESE behavior inspires an efficient approach to empirically predict the performance of DUV lasers by assessing the lasing properties of SSE from unprocessed laser wafers.

OD-Mon-P12* - Surface-emitting InGaN laser based on circular Bragg resonator

3. Optical devices

Yangzhi Tan[1]
Hoi Wai Choi[1], Kai Wang[2]
[1] Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong, China
[2] Department of Electrical and Electronic Engineering, Southern University of Science and Technology, Shenzhen, China

Abstract text: InGaN-based surface-emitting lasers (SELs) represent promising coherent light sources for displays, optical storage, and communications. While conventional InGaN SELs typically adopt vertical-cavity structures (VCSELs) incorporating top and bottom distributed Bragg reflectors (DBRs) for optical confinement, these devices encounter critical limitations: (i) thermal management challenges stemming from the intrinsic low thermal conductivity of DBR materials, (ii) suboptimal vertical optical field confinement and (iii) complex fabrication processes associated with DBR deposition.

This work presents a novel approach based on GaN thin films, wherein the construction of a circular Bragg resonator (CBR) structure achieves superior two-dimensional optical field confinement and a pronounced Purcell effect, with a Purcell factor approximating 17, significantly boosting radiative rate/efficiency through spontaneous emission coupling. Besides, the robust confinement of the field distribution in the InGaN CBR laser inherently facilitates its integration into compact two-dimensional arrays. These advantages position the InGaN CBR laser as a viable solution for applications requiring high-speed, low-power, and scalable coherent light emission.

OD-Mon-P13* - Structural Modifications of GaN/AlGaN Nanowire Photonic Crystal Laser to Improve the Top Output Efficiency

3. Optical devices

Dishiti Gupta[1]
Tron Arne Nilsen[1], Bjørn-Ove Fimland[1], Helge Weman[1]
[1] Department of Electronic Systems, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway

Abstract text: High-efficiency surface-emitting UV laser sources (~ 200 - 400 nm) are in high demand for applications such as water purification, disinfection, sensing, and non-line-of-sight communications. GaN/AlGaN nanowires (NWs) are a promising choice due to their stability, wavelength tunability, and dislocation-free structure [1].

Periodically arranged NWs form a two-dimensional (2D) photonic crystal (PhC), which forms the basis for NW PhC lasers. This study explores various methods to enhance light extraction from the top surface, characterized by the top output efficiency (TOE) of a top-emitting GaN/AlGaN NW PhC laser structure through 2D and 3D simulations. The simulation model only accounts for losses in the out-of-plane direction and does not incorporate absorption. The NWs are directly grown on a sapphire substrate using a hole mask. Conventionally, a distributed Bragg reflector (DBR) is used to improve TOE by increasing reflectivity from the bottom side [2], achieved by inserting the DBR below the NW. A SiO_2/Si_3N_4 DBR significantly enhances TOE, increasing it from 60% without a DBR to over 90% with four periods. However, the fabrication and NW growth on a dielectric DBR can be challenging, necessitating the exploration of alternative methods to improve TOE. Tapering the cylindrical NW structure towards the substrate (anti-tapered NW) reduces the effective refractive index at the bottom, pushing the mode upwards, improving TOE and mode confinement. When combined with a DBR, a tapered NW shows less improvement in TOE than a cylindrical NW, possibly due to the scattering of light by the taper. However, the Q-factor for the tapered NW is an order of magnitude higher than the cylindrical NW with the DBR. The thickness of the Si_3N_4 hole mask (used for positioned growth of the NWs) impacts the TOE for cylindrical and tapered NW structures. The TOE reduces to around 30 % for cylindrical NWs with mask thicknesses in the 20-50 nm range and increases to above 60 % for 100 nm thickness. For the tapered NW, mask thicknesses of 30–50 nm should be avoided due to reduced TOE.

In summary, a cylindrical NW with a bottom DBR has higher TOE, but a tapered NW has much lower losses, potentially lowering the lasing threshold. Mask thickness also significantly impacts TOE.

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OD-Mon-P14* - Comparative analysis of three-dimensional optical simulation methods for designing blue Photonic-Crystal Surface-Emitting Lasers

3. Optical devices

Arstan Bisianov[1]
Daniel Stoll[1], Frederik Lüßmann[1], Jana Hartmann[1], Andreas Waag[1]
[1] Nitride Technology Center (NTC), Institute of Semiconductor Technology, Technische Universität Braunschweig, Germany

Abstract text: Blue GaN-based Photonic-Crystal Surface-Emitting Lasers (PCSELs) are highly functional light sources combining unique features such as short wavelength, high beam quality and directionality, as well as high brightness and coherence levels. Future applications of such lasers include underwater LiDARs and processing of hard-to-handle materials [1,2]. The development of GaN-based PCSELs has significantly accelerated in recent years [3-7], both in fabrication and design optimization.

Various numerical methods have been established for the design optimization of PCSEL lasers, including 3D Coupled-Wave Theory (CWT) [9,10], Rigorous Coupled-Wave Analysis (RCWA) [11,12], Iterative Weighted Index Method [13], and the more rigorous Finite-Difference Time-Domain (FDTD) approach. However, a systematic comparative analysis of these approaches is largely missing or scarcely represented in the literature. Therefore, in this study, we compare the most established numerical methods, including 3D CWT, RCWA, and FDTD, in application to blue GaN-based PCSELs. The validity of these methods is evaluated in terms of precise identification of resonant modes, photonic crystal induced radiation losses, coupling coefficients, as well as simulation speed of each method. To spot any limitations of each method, we vary some PCSEL design parameters, namely photonic crystal geometry and performance parameters like mode confinement factors and electrode reflectivity. Our study directly compares accuracy and speed of these methods, enabling a more informed decision when designing PCSEL devices, particularly those implemented in III-nitride systems.

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OD-Mon-P15* - Heterogeneously integrated GaN photonic crystal laser on Si (100)

3. Optical devices

Xiaoping Zhou[1]
Xingfei Zhang[1], Ran Yao[1], Hua Yang[1], Yiyun Zhang[1], Xiaoyan Yi[1], Junxi Wang[1], Jinmin Li[1]
[1] Research & Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

Abstract text: The fabrication of photonic crystal structure based on GaN suffers from processing difficulties due to the chemical inertness of III nitride materials and the short lattice in the visible wavelength range. In this work, a method combing a series of wafer bonding, laser lift-off and chemical mechanical polishing process, has been proposed to transfer the nitrides from patterned sapphire substrate onto Si (100) substrate. The GaN epilayer transferred is uniformly thinned down to 180 nm with a root mean square surface roughness as low as 1.77 Å, which means strong coupling and low scattering loss. During the transfer process, the distributed Bragg reflector or metallic reflecting layer has been utilized to provide the highly vertical optical confinement, avoiding the complexity of fabricating air-bridge structure. The photonic crystal cavity is designed and simulated by plane wave expansion method and finite difference time domain calculation strategies. The electron beam lithography and inductively coupled plasma-reactive ion etching are employed to fabricated the GaN based photonic crystal laser. Based on the platform, an array of photonic crystal cavities with diverse cavity types (including H0, H1, H2 and H3) are fabricated. The photonic crystal cavity demonstrates a high Q factor around 510 nm. The transfer strategy provides a promising platform for fabrication microcavities for nitride-based integrated photonics.

OD-Mon-P16* - Low Threshold and Continuous-Wave Whispering Gallery Mode Laser with Single-Mode Operation

3. Optical devices

Feifan Xu[1]
Jushi Liu[2], Zhe Zhuang[2], Tao Tao[1], Rong Zhang[3], Bin Liu[1]
[1] School of Electronic Science and Engineering, Nanjing University, Nanjing, China.
[2] School of Integrated Circuits, Nanjing University, Suzhou, China
[3] Xiamen University, Xiamen, China

Abstract text: Chip-scale, compact laser sources are pivotal for advancing emerging technologies such as on-chip optical communications, photonic computing, and quantum optics. Among these, whispering gallery mode (WGM) micro-cavity lasers have garnered significant attention due to their high quality (Q) factors, small mode volumes, and straightforward fabrication. They are increasingly recognized as indispensable components in photonic integrated circuits (PICs), where scalability, low-power operation, and robust performance are critical. Addressing challenges in mode control and fabrication methods is essential for unlocking the full potential of WGM micro-cavity lasers in practical applications.

In this work, we present a novel and scalable approach to fabricate high-performance WGM micro-cavity lasers on GaN structures. A key innovation lies in the careful design of an ITO cladding layer and implementation of an optimized dry etching process to achieve smooth sidewalls, which significantly enhances optical confinement and facilitates efficient WGM excitation. As a result, we reported an impressive slope efficiency of 0.36 W/A, indicative of the strong optical gain within the micro-cavity. We also used this technique to demonstrate micro-disk lasers in different diameters ranging from 10 to 160 μm. All these lasers exhibit consistently low thresholds, with the minimum threshold current density falling below 1 kA/cm², which was much lower compared to previous reports.

Another important innovation involves the effective mitigation of higher-order modes via the introduction of a central circular aperture in the micro-disk resonator. This ring-like structure substantially reduces mode competition, ensuring that the primary WGM mode dominates the emission spectrum. Under electrical injection, the devices exhibit an active Q factor of 10744, highlighting their low optical losses and superior cavity finesse. Collectively, the demonstrated scalability, low lasing threshold, and efficient mode selectivity underscore the strong potential for advancing practical photonic applications such as biosensing, optical interconnects, and quantum information processing.

OD-Mon-P17* - Absorption spectroscopy of the absorber section of multi-section blue laser diodes

3. Optical devices

Shemshat Kerimova[1]
Anna Kafar[2], Szymon Stanczyk[2], Łucja Marona[2], Piotr Perlin[2], Ulrich T. Schwarz[1]
[1] Institute of Physics, Chemnitz University of Technology, Chemnitz, Germany
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: In laser diodes (LDs) with multiple sections or in photonic integrated circuits (PICs), individual waveguide sections can act as optical gain or absorption section, depending on the bias voltage. Multi-section LDs have been employed for short-pulse generation in different operation regimes, depending mostly on the carrier life time in the absorber section. In PICs the absorber section can be used for a fast modulation of light intensity.

We fabricated blue light (λ=425 nm) emitting LDs with gain and absorber sections using MOVPE and graded-index design [1]. The lateral single mode waveguide (1 mm long) had two electrically insulated p-contacts and a common n-contact through the substrate. Length ratios of gain and absorber sections were 6/4, 7/3, and 8/2. Threshold current is 65 mA when both sections are connected. Leakage current between the two p-contacts was < 1 µA for a bias voltage difference of 10 V, with V_{bias}=-6 V at the absorber and +5 V at the gain section. Optical gain spectra were measured by Hakki-Paoli method.

When both sections are connected, we observe the typical gain spectra of a LD. With reduced current in the absorbing (shorter) section, absorption increases up to a maximum absorption at $I_{absorber}$ = 0 mA and V_{bias}=+2 V. When bias voltage is varied between V_{bias}=+2 V to V_{bias}=-6 V, the absorption is decreasing with increasing negative bias. Such behavior has been observed before and was explained by a blue-shift of the absorption edge due to quantum-confined Stark effect when the piezoelectric field in the quantum well is compensated by the field or the revers-biased pn-junction [2]. Current in the absorber section remained small (< 10 µA) in all cases, meaning that no large photocurrent was generated by absorbing light from the gain section for the below-threshold forward current. Modulation speed in this regime should be limited by the capacity of the pn-junction rather than by charging the active region, and therefore fast. We observe a variation of the absorption between -5 cm^{-1} and -35 cm^{-1}, corresponding to attenuations of 86% and 35% in the 300 µm long absorber section. Therefore, longer absorber sections are necessary in order to reach a considerable dynamic range for an intensity modulation in PICs.

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OD-Mon-P18* - Effect of Current Spreading on the Operation of Nitride-Based Broad-Area Stacked Laser Diodes with a Tunnel Junction

3. Optical devices

Olga Soboleva[1]
Mikhail Rudinsky[1], Kirill Bulashevich[1]
[1] Semiconductor Technology Research d.o.o. Beograd

Abstract text: In recent years, there has been increasing interest in high-power III-nitride laser diodes (LDs) emitting in near-UV and blue wavelength ranges for industrial and medical applications, as well as light sources for LiDARs [1]. One of the promising ways to increase optical output power is to integrate two or more laser emitters via tunnel junctions (TJs), which is widely used in near-infrared LDs and III-nitride LEDs.

In this paper, we used the hybrid approach [2] to simulate AlGaN/GaN/InGaN heterostructure with a stack of two LDs integrated via TJ. This approach in application to LD could be described as follows: 1) separate 1D drift-diffusion simulations of a single laser emitter and TJ using SiLENSe [3]; 2) 2D/3D current spreading simulation in the whole structure using a simplified transport model [3], where the previously obtained current-voltage characteristics are used as boundary conditions.

A good agreement with experimental data was achieved for the single emitter [1], closely matching the value of 12 W peak power at 14 A pulsed current. Using this data, the model predicts that a high-resistance TJ, as reported in [1], causes significant side current spreading in the bottom LD, reducing its efficiency. With lower TJ resistance, as simulated for the ideal case of TJ from [1] with complete Mg activation, current density spreading outside the stripe is reduced but still significant. Specifically, at currents below the lasing threshold, the portion of current flowing under the 70 μm stripe near the top and bottom active regions (ARs) is 94% and 66%, respectively, for low-resistance TJ, compared to 91% and 23% for high-resistance TJ. Moreover, the effect of current crowding is more prominent in the top LD for high-resistance TJ.

In summary, the model shows that high TJ resistance leads not only to side current spreading in the bottom LD, but also to a highly inhomogeneous current density distribution in the top LD. To suppress these effects, a structure with buried blocking layers [4] might be used, in addition to reducing TJ resistance.

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OD-Mon-P19* - Fabrication of Horizontally Stacked AlN/SiNx Transverse Quasi-Phase Matching Waveguide for Integrated Wavelength Converter

3. Optical devices

Hiroto Honda[1]
Masahiro Uemukai[1], Tomoyuki Tanikawa[1], Ryuji Katayama[1]
[1] Graduate School of Engineering, The University of Osaka, Suita, Osaka 565-0871, Japan

Abstract text: The development of photonic integrated circuits (PICs), which enhance scalability and stability in optical systems, is driven by photonic quantum information processing technology. Classical PICs composed of Mach–Zehnder interferometers (MZIs) can be upgraded to quantum PICs by integrating quantum light sources such as wavelength converters that generate photon pairs or squeezed light. AlN with second-order optical nonlinearity is a promising material for wavelength converters and quantum PICs platform. A horizontally stacked +*c*-AlN/SiN_x transverse quasi-phase matching waveguide enhances the nonlinear coupling coefficient κ lather than κ of a +*c*-AlN waveguide which only use modal dispersion phase matching.[1] The horizontally stacked structures can be fabricated using standard CMOS processes such as chemical mechanical polishing (CMP) and overlay lithography and allows seamless and easy connection with +*c*-AlN-based MZIs. In this study, the fabrication of horizontally stacked AlN/SiN_x waveguides will be reported.

A +*c*-AlN layer with a thickness of 520 nm was grown on a sapphire substrate by metal organic vapor phase epitaxy. An AlN center core was formed by inductive coupled plasma-reactive ion etching (RIE) using an SiO_2 mask. The width of the center core was 520 nm and the taper angle was 74°. No special care was taken to improve the verticality of the sidewalls to deposit void-free SiN_x layer on the AlN core's sidewalls. The SiN_x layer other than the region protected by photoresist where the side cores are formed were etched down to the CMP stop depth by capacitive coupled plasma (CCP) -RIE. The RIE step avoids unnecessary polishing of the whole SiN_x surface and allows the reagions to be planarized to be polished preferentially. After polishing, a flat SiN layer was obtained and the root mean square roughness is 0.78 nm over a 5×5 μm^2 region. The overlay alignment electron beam lithography was performed and SiN_x side cores with width of 1.1-1.5 μm were successfully formed by CCP-RIE. Device design and optical experiments will also be reported on the day.

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OD-Mon-P20 - Supercontinuum generation in thick AlN-on-sapphire waveguides: expanding the spectrum toward the mid infrared

3. Optical devices

Samuele Brunetta[1]
Samantha Sbarra[2], Jean-François Carlin[1], Nicolas Grandjean[1], **Raphaël Butté**[1], Camille-Sophie Brès[2]
[1] Laboratory of Advanced Semiconductors for Photonics and Electronics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[2] Photonic Systems Laboratory, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Abstract text: Supercontinuum generation (SCG) uses high-energy pulsed sources to generate a broad-bandwidth signal with applications covering a wide range of fields including precision spectroscopy and metrology. In recent years, SCG in photonic integrated devices—such as waveguides—has been extensively explored due to the higher mode confinement than in bulk crystals. Among the most common materials for integrated photonics, aluminum nitride (AlN) stands out due to its wide transparency window (200 nm – 5.5 μm), its intrinsic second- and third-order optical nonlinearities, and its high thermal conductivity, making it suitable for on-chip broadband SCG.

In this work, we study SCG on epitaxial AlN-on-sapphire waveguides, with a particular focus on extending the spectral coverage. In particular, we show how using thicker AlN epilayers and employing pulsed sources at wavelengths longer than 1550 nm can be beneficial for energy transfer toward the mid infrared (MIR).

Our AlN epilayers were grown by metalorganic-vapor phase epitaxy either on thin sputtered AlN buffer on *c*-plane sapphire, or on a 1-μm-thick commercial AlN-on-sapphire epilayers, allowing us to obtain high-quality layers up to 1.3 μm thick. Moreover, after defining the device pattern with electron-beam lithography, we fully etched our waveguides, in order to obtain an improved mode confinement. With our fabrication process we can achieve propagation losses down to 0.24 dB/cm at 1550 nm, as extracted from intrinsic quality factors up to 1.6 million in microring resonators.

We first probed our waveguides using a femtosecond-pulsed laser centered 1560 nm in TM polarization. In addition to long and short dispersive waves, we could observe further nonlinear effects, such as second-, third- and fourth-harmonic generation, broadening the spectrum toward the visible and UV. We tested waveguides of different heights, obtaining increased spectral coverage in the infrared when using thicker epilayers. We also probed our waveguides with a pump laser at 2090 nm, showing a further bandwidth expansion and increased dispersive wave amplitude. This way, we could obtain a broad supercontinuum (SC) spectrum ranging from 550 nm up to over 4000 nm. In conclusion, our results showcase AlN-on-sapphire as a promising platform for on-chip spectrometry and metrology, due to its tunable SC spectral coverage from the visible to the MIR.

OD-Mon-P21 - Terahertz electro-optical modulator based on two-dimensional plasmon excitation in AlGaN/GaN heterostructures

3. Optical devices

Daniil Pashnev[1]
Justinas Jorudas[1], Vytautas Janonis[1], **Irmantas Kašalynas**[1]
[1] Center for Physical Science and Technology, Sauletekio av. 3, LT-10257 Vilnius, Lithuania

Abstract text: Two-dimensional (2D) plasma oscillations in semiconductor inversion layers offer wide applications in the THz regime [1]. Plasmonics in the THz range facilitates the development of tunable phase shifters [2] and optical modulators [3]. Beyond graphene plasmonic devices, grating-gated AlGaN/GaN high electron mobility transistor (HEMT) structures have demonstrated the ability to sustain 2D plasma oscillations from liquid nitrogen up to room temperatures [4]. The resonant frequency of 2D plasmons is governed by 2D electron density, which is controlled by biasing the grating gate allowing to modulate density by several orders of magnitude before the plasmonic device transition to the localized phase [5], [6].

In this work, we experimentally investigated 2D plasmon oscillations in grating-gated AlGaN/GaN HEMT structures within the THz range. Amplitude and phase transmission spectra were measured under external gate bias using the THz time-domain system (Teravil, T-SPEC 800). The results highlight the capability of these structures to tune electrically the amplitude and phase of incoming THz radiation under modulation of the 2D electron density via applied external bias.

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OD-Mon-P22 - Scalable GaN photonic-phonoinc integrated circuitry for reconfigurable signal processing

3. Optical devices

Liang Zhang[1]

[1] Research and Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

Abstract text: The photon-phonon interaction underpins critical functionalities in diverse applications, including optical modulation, quantum transduction, and precision metrology. Integrated photonic-phononic devices offer a promising pathway to enhance interaction strength while enabling large-scale integration. However, despite significant progress in demonstrating enhanced interactions, material limitations have hindered the realization of scalable photonic-phononic circuits. Here, we address this fundamental challenge through gallium nitride-on-sapphire platform, which enables simultaneous sub-wavelength confinement of optical and acoustic fields without requiring suspended structures. This breakthrough allows efficient excitation, flexible routing, and reconfigurable manipulation of both optical and acoustic domains. Leveraging precisely controlled photon-phonon interactions and strong piezoelectric coupling, we demonstrate reconfigurable conversion of frequency-multiplexed RF and optical signals mediated by acoustic waves. Our work establishes a versatile platform for high-performance photonic-phononic systems, combining exceptional efficiency, multifunctional capabilities, and scalable integration.

OD-Mon-P23* - High transmission of circularly polarized light and circular dichroism with all-dielectric metamaterial

3. Optical devices
Ting Zhi[1]
Jin Wang[1], Junjun Xue[1], Tao Tao[2]
[1] Nanjing University of Posts and Telecommunications, Nanjing, China
[2] Nanjing University, Nanjing, China

Abstract text: Circular dichroism is a crucial area in polarization control. It pertains to the differential transmission or reflection coefficients of optical devices for left-circularly polarized (LCP) and right - circularly polarized (RCP) light. This phenomenon has significant applications in diverse fields like quantum, medicine, medicinal chemistry, and biology. However, the chiroptical signals from natural materials are extremely weak, making it difficult to obtain high-quality LCP and RCP light.

In this study, a Z-axis constant cross-section meta-atom structures composed of combined square and semicircular shapes were designed, which achieved high ratio of transmission or reflection and CD values at the blue light range. At the wavelength of 460 nm, the designed meta-atom structure converted most LCP light into RCP light, while reflecting almost all RCP light. Moreover, opposite results can be obtained when incident from the backside of the meta-atom structure. According to simulation results, structure with asymmetrically assembled semicircles and squares can achieve extremely high transmission of LCP and reflection of RCP. Because linearly polarized light can be considered as the superposition of LCP and RCP light, the metamaterial can function under any linear or circular polarization to produce a single circularly polarized light. The geometric phase can be controlled by designing the orientation angle of meta-atoms, achieving modulation of the optical field. By geometric phase, the 2π phase distribution can be achieved while maintaining a transmission and CD value mostly above 0.9. This metamaterial structure can combine the functions of a half-wave plate, a quarter-wave plate, and an optical field modulator. The results of the proposed structure can provide new ideas for designing high-transmission structures and optical integrated devices.

OD-Mon-P24* - GaN homogeneous circular polarizer metasurface for surface-emitting lasers

3. Optical devices

Li-Sheng Hu[1]
Yong-Wei Lai[1], Cheng-Yi Tsai[1], Tien-Chiu Chen[1], Wen-Hsuan Hsieh[1], Tien-Chang Lu[1], Chia-Yen Huang[1]
[1] National Yang Ming Chiao Tung University, No. 1001, Daxue Rd., East Dist., Hsinchu City 300, Taiwan

Abstract text: Circular-polarized (CP) light has many advantages for many applications in optical communication, stereoscopic display, bio-imaging, and many others. However, the natural generation of CP light out of semiconductor emitters is almost impossible since the crystals are achiral. The attachment of passive elements like QWP results in a bulky module and requires a specific alignment of the linear polarization direction. Therefore, a single-layer homogeneous circular polarizer (HCP) metasurface, which is insensitive to the incident linear polarization angle, is desired. If the metasurface is made of GaN, it can be monolithically integrated with the surface-emitting lasers grown on the GaN substrate backside.[1,2]

In this report, we designed and fabricated a GaN-based metasurface that can impose the right-CP (RCP) component and left-CP (LCP) component of laser irradiation to independent phase profiles. For example, we can retain the RCP component of a linear-polarized laser on the optical axis while deflecting the LCP component away with a large angle of 75° after passing through the metasurface. The prominent aliasing effect due to the short wavelength and large deflection angle is suppressed by setting the phase gradient along a high-index reciprocal vector. In the simulation, the average degree of circular polarization out of the HCP is 0.95 from all linear polarization, while that from the experiment is 0.88. The average power efficiency is 50% in the simulation and 40% in the experiment. The schematic processing flow and the optical characterization results are shown on the supplemental page. More details about design methodology and challenges in the device integration will be discussed at the conference site.

OD-Mon-P25* - Breaking the Surface and Unlocking Superior Performance of Indium Rich Edge Emitting InGaN GaN Green LEDs

3. Optical devices

Subhranshu Sekhar Sahu[1]
Soumyadip Chatterjee[2], Aasheesh Sharma[2], Suddhasatta Mahapatra[1], Apurba Laha[2]
[1] Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India
[2] Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India

Abstract text: In this study, we investigate and compare the electrical and optical performance of surface-emitting (SLED) and edge-emitting (ELED) InGaN/GaN green light emitting diodes. The devices were fabricated using a top-down (TD) dry etching technique via inductively coupled plasma reactive ion etching (ICPRIE) process on InGaN/GaN heterostructures, incorporating a multiple quantum well (MQW) active region. Structural differences were analysed, with SLED utilizing a top-emitting structure and ELED employing a waveguide-based edge emission design. Current-voltage (I-V) characteristics reveal that ELED exhibits superior performance, with a lower turn-on voltage (~2.5 V) compared to SLED (~3 V), indicating improved carrier injection efficiency. Additionally, ELED shows higher forward current at a given voltage, suggesting reduced series resistance and enhanced current spreading. Under reverse bias, both devices demonstrate low leakage currents (10^{-9} to 10^{-11} A), with SLED exhibiting slightly lower values, likely due to reduced tunnelling effects. The superior electrical properties of ELED are attributed to its waveguide-enhanced carrier transport and reduced non-radiative recombination at the surface. Capacitance-voltage (C-V) measurements further support these findings, revealing frequency-dependent carrier-induced defect saturation in ELED. At low frequencies (10 kHz), a capacitance peak appears, indicating significant charge trapping and defect interaction, while at higher frequencies (100 kHz and 1 MHz), the capacitance response flattens, suggesting that slow defect states cannot follow the AC signal. This behaviour highlights the role of defect saturation in stabilizing carrier dynamics and reducing non-radiative recombination, enhancing overall performance. The waveguide structure in ELED improves carrier confinement and transport, minimizing defect-related losses compared to SLED. Furthermore, ELED has a narrower FWHM of electroluminescence (EL) intensity than SLED, signifying more directional emission. The superior performance of ELED highlights its potential for high-efficiency, high-power applications in solid-state lighting, displays, quantum encryption, and ultra-fast optical networks. These findings provide valuable insights into optimizing InGaN/GaN LED architectures for next-generation optoelectronic devices.

OD-Mon-P26 - Weak Polarization Electric Field LEDs with Enhanced Efficiency on Polar Plane

3. Optical devices

Gaoqiang Deng[1]
Jingkai Zhao[1], Changcai Zuo[1], Yusen Wang[1], Haozhe Gao[1], Yuantao Zhang[1]
[1] State Key Laboratory of Integrated Optoelectronics, JLU Region, College of Electronic Science and Engineering, Jilin University, 2699 Qianjin Street, Changchun 130012, People's Republic of China

Abstract text: Quaternary InAlGaN exhibits great potential in III-nitride polarization engineering and strain modulation due to its high degree of freedom. It can be utilized to reduce the polarization electric field in multiple quantum wells (MQWs) by adjusting the composition. However, to achieve high-efficiency weak polarization electric field (PEF) InAlGaN-based light-emitting diodes (LEDs) remains a challenge on polar plane.

Here, we propose an alternative approach by employing InGaN/AlGaN digital alloy (DA) superlattices as the barrier layers of MQWs instead of quaternary InAlGaN, enabling the efficiency enhancement of InAlGaN-based LEDs grown by pulse-growth mode of metal organic chemical vapor deposition (MOCVD). We investigate the structural quality and optical performance of both InGaN/AlGaN DAs and InGaN/DAs MQWs. By optimizing the pulse-growth conditions, we successfully epitaxially grow InGaN/DAs MQWs with PEF as low as 0.5 MV/cm. Further, using industrial mass-production MOCVD, we realize the industrial-scale preparation of weak-PEF InAlGaN-based LEDs with peak external quantum efficiency up to 15%, which is the highest value in current studies of its kind. Importantly, weak-PEF InAlGaN-based LEDs have strong carrier confinement capability akin to quantum dots because they have a carrier lateral diffusion length obviously shorter than conventional nitride LEDs, and therefore show great application potential in micro-LED display. This study demonstrates a reliable epitaxy approach for the preparation of high-efficiency weak-PEF LEDs, which can be expanded to all III-nitride LEDs.

OD-Mon-P27* - Micro-Transfer Printing of InGaN-based Red Micro-Light-Emitting Diodes on Silicon for Display Applications

3. Optical devices

Zhi Li[1]
James O'Callaghan[1], changhao Li[1], Bumjoon Kim[2], Abhinandan Hazarika[1], Muhammet Genc[1], Soo Min Lee[2], Drew Hanser[2], Brian Corbett[1]
[1] Tyndall National Institute, University College Cork, Cork, T12 R5CP, Ireland
[2] Veeco Instruments Inc., Somerset, NJ 08873, USA

Abstract text: InGaN-based red light-emitting diodes (LEDs) have attracted much attention owing to the demand for manufacturing of high-efficiency displays including the emerging virtual reality and augmented reality applications. Compared to their classical AlGaInP-based counterparts, InGaN red LEDs show promise especially at the small chip sizes due to the reduced surface recombination issues. Assembling a massive number of red-green-blue devices for displays requires a mass transfer technique. Among the existing technologies, the micro-transfer printing has been considered as an effective approach to integrating different colour emitters due to its highly precise and scalable process. However, the reported demonstration are typically based on InGaN-based blue and green LEDs and AlGaInP-based red LEDs, which have distinct fabrication process details including the releasing etch due to the different material properties.

In this work, we utilise InGaN-based red LEDs grown on a 200 mm diameter Si substrate and we demonstrate the successful micro-transfer printing of these devices (30x50 μm^2) and their integration with the blue and green counterparts for display applications. By working with the same material platform, the common device preparation and releasing process was applied to all the red, green and blue (RGB) LED-on-Si wafers. Based on the anisotropic etching of (111) Si in the tetramethylammonium hydroxide (TMAH) solution, the InGaN red micro-LEDs were successfully released from the Si substrate. The micro-transfer printing was performed using a 50x50 array stamp, resulting in 10,000 device transfer (4 prints) with a yield of ~96%. The failure analysis of the missing devices was also conducted. This is our initial test and we expect that the yield can be improved further with an optimized process. Individual red micro-LEDs were also transfer-printed onto a glass substrate and connected up with large metal bond pads. The optical and electrical properties of these LEDs were tested and compared to those before printing. To our best knowledge, this is the first report of micro-transfer printing with the InGaN-based red micro-LEDs.

OD-Mon-P28* - Using microLED Arrays as an Analysis Tool for Improving Heterogeneous Integration Yields

3. Optical devices

Georg Schöttler[1]
Maximilian Vergin[1], Rany Miranti-Augustin[1], Florian Meierhofer[1], Jana Hartmann[1], Andreas Waag[1]
[1] Nitride Technology Center, Institute of Semiconductor Technology, Technische Universität Braunschweig, 38106 Braunschweig, Germany

Abstract text: Monolithic microLED arrays paired with CMOS backplanes represent a leading solution for high brightness microdisplays, including emerging applications such as optical neuromorphic computing. Each GaN-based microLED is driven by a dedicated Si-based driver, requiring reliable, high-density interconnects. This chip connection technology, an integral part of advanced packaging, is prevalent in modern chiplet-based integrated circuits like GPUs and SoCs. Just like for microLED modules, on the order of a million chip-to-chip interconnects in low micron range are required.

This massively increases the risk of defects, caused by, e.g., CTE (coefficient of thermal expansion) mismatch, chip non-coplanarity, or functional layer failures. Today, yield is a key issue for the fabrication of microLED displays. Although complex methods such as FIB (focused ion beam) can help investigate these defects, much can be learned from analyzing the optical emission patterns of the microLEDs located at each interconnect. Identifying the key factors affecting yield is essential for process control, in particular for monolithic microLED arrays, where pixel failures cannot be tolerated and hence an extremely high bond yield is essential due to the lack of repair options. Insights gained can then be transferred to GPUs or SoCs.

We have successfully integrated numerous GaN microLED arrays with interposers fabricated on silicon substrates, mimicking the final CMOS backplane interface. Indium bump bonding was used as a commonly employed bonding method to achieve fine pitch interconnects for substrates of diverging CTE. The quality of the heterogeneous bonding is evaluated by analyzing the optical emission pattern of the microLED arrays. We will discuss the process development based on optical emission patterns along with various interposer wiring schemes designed to tackle specific chip integration challenges.

In this contribution, we demonstrate that the study of emission patterns of microLED arrays is an effective way to evaluate hybrid interconnect yield of bonded chip stacks. This approach yields rapid results and immediate feedback, in contrast to traditional purely electrical characterization techniques, which can be adapted to other chip-chip stacks.

OD-Mon-P29* - GaN-based Freestanding Micro-LEDs with GHz Bandwidth and Low Efficiency Droop for Visible Light Communication

3. Optical devices

Jinpeng Huang[1]
Ting Zhi[2], Tao Tao[1], Bin Liu[1]
[1] Jiangsu Provincial Key Laboratory of Advanced Photonic and Electronic Materials, School of Electronic Science and Engineering, Nanjing University, Nanjing, China
[2] College of Electronic and Optical Engineering and College of Microelectronics, Nanjing University of Posts and Telecommunications, Nanjing, China

Abstract text: Keywords: Freestanding micro-LEDs, quantum barrier, modulation bandwidth, efficiency droop, visible light communication.

Abstract: Visible light communication (VLC) based on micro light-emitting diodes (micro-LEDs) offers an energy-efficient method for the explosive data transmission. However, the severe quantum-confined stark effect (QCSE) and carrier localization make it challenging for micro-LEDs to achieve both high modulation bandwidth and high external quantum efficiency (EQE). Herein, GaN-based freestanding micro-LEDs with varying quantum barrier thicknesses were designed and fabricated. The thinner quantum barriers effectively reduce the QCSE and improve the carrier transport, resulting in high modulation bandwidth and less efficiency droop. Homoepitaxial growth of micro-LEDs give birth to further improved modulation bandwidth and optical power due to lower defect density and improved thermal dissipation. The -3 dB bandwidths of the 10 μm- and 20 μm-diameter freestanding micro-LEDs exceed 1.03 GHz and 823 MHz, respectively. A high optical power of 5.54 mW and a data rate of 4.08 Gbps, while maintaining a relatively high EQE of 4.17%, were achieved on 20 μm-diameter devices. The proposed methods systematically improve the modulation bandwidth and luminescence efficiency, demonstrating significant potential for free-space visible light communication.

Corresponding author: ttao@nju.edu.cn, bliu@nju.edu.cn

OD-Mon-P30* - Unraveling Optical Amplification by Optimizing Nanorod LED Designs for High-Efficiency Micro-LED Displays

3. Optical devices

Min-Seok Lee[1]
Sung-Un Kim[1], Dae-Young Um[1], Jeong-Kyun Oh[1], Vignesh Veeramuthu[1], JaeJae-Hong Ju[1], Se-Bee Shin[1], Cheul-Ro Lee[1], Yong-Ho Ra[1]
[1] Division of Advanced Materials Engineering, College of Engineering, Jeonbuk National University (JBNU), Jeonju, Republic of Korea

Abstract text: The advancement of next-generation display technologies, including virtual reality (VR), mixed reality (MR), and extended reality (XR), depends on refining micro-LEDs with ultra-high-resolution pixel structures. Gallium nitride (GaN)-based semiconductors, known for their exceptional optoelectronic properties and physicochemical stability, are particularly well-suited for these applications. Precision etching techniques have enabled the development of strain-relaxed nanorod LED architectures, significantly improving internal quantum efficiency and facilitating vertical photon extraction. However, the mechanisms underlying optical amplification in nanorod LEDs remain insufficiently understood. This study explores spontaneous optical amplification in nanorod LEDs through micro-photoluminescence (micro-PL) spectroscopy. Variations in optical feedback among different nanorod emitters reveal that some configurations achieve substantial enhancement, while others show limited improvement. To better understand these differences, three-dimensional finite-difference time-domain (3D FDTD) simulations were conducted to assess how structural parameters affect light extraction and emission efficiency. The results highlight that optimizing nanorod geometries can substantially enhance micro-LED performance. Furthermore, time-resolved photoluminescence (TRPL) spectroscopy was used to examine the role of photon recycling (PR), a nonlinear optical effect that occurs in high-density regions of photo-excited carriers. Findings indicate that PR significantly enhances spontaneous emission, particularly in nanorod LEDs with optimized architectures, which exhibit an 11-fold increase in luminous output under spontaneous excitation compared to non-optimized counterparts. These results confirm PR as a crucial factor in improving radiative efficiency and overall light emission in micro-LEDs. By optimizing nanorod structures and elucidating amplification mechanisms, this research advances micro-LED technology for next-generation displays. These improvements enable brighter, more efficient panels, crucial for high-performance VR, MR, and XR applications, driving the future of immersive display systems.

OD-Mon-P31* - Elimination of size effects in InGaN quantum dot cyan-green Micro-LEDs by constructing a full-M-plane hexagonal structure

3. Optical devices

Peng Zhang[1]
Haibing Qiu[2], Wenxian Yang[3], Jianjun Zhu[3], Shibing Long[1], Shulong Lu[3]
[1] School of Microelectronics, University of Science and Technology of China
[2] State Key Laboratory of Widegap Semiconductor Optoelectronic Materials and Technologies, North University of China
[3] Key Lab of Nanodevices and Applications, Suzhou Institute of Nano-Tech and Nano-Bionics (SINANO), Chinese Academy of Sciences (CAS)

Abstract text: GaN-based micro-light-emitting diodes (micro-LEDs) are critical for lighting and display applications due to their high efficiency and stability. However, it has been a challenge to alleviate the reduction of the external quantum effect (EQE) of micro-LEDs with decreasing size. This is attributed to an increase in the Shockley-Read-Hall (SRH) non-radiative recombination rate of the sidewall. Due to the size effects, it is more difficult to prepare efficient micro-LEDs with decreasing the mesa size. In this work, Micro-LED epi-wafers with using InGaN quantum dots (QDs) as active layer materials were grown by plasma-assisted molecular beam epitaxy (PA-MBE), and full-M-sided hexagonal structure micro-LEDs were prepared. We fabricated the micro-LED array with the full-M-sides hexagonal structure and repaired etching damage on the sidewall by being chemically treated with tetramethylammonium hydroxide (TMAH) solution. Most of the surface defects caused by etching were eliminated, and the etching damage can be further reduced by using QDs as an active region. Thus, the efficiency of the micro-LED at low injection current density is improved, and the size effect is eventually overcome. Compared with the 20 μm micro-LED array, the peak EQE of the 10 μm micro-LED array was improved by 79 %, reaching 0.83 % at 11 A/cm^2. We demonstrate that constructing full M-side structures can overcome the size effect in InGaN QDs-based micro-LEDs. Notably, the cyan-green micro-LEDs fabricated by this method exhibited low-efficiency-drop. In addition, QDs-based micro-LED exhibits excellent wavelength stability with increasing inject current density. This work provides a new way to fabricate high-efficiency micro-LEDs.

OD-Mon-P32 - Laser Annealing-Driven InGaN Quantum Dot Formation in MQWs for High-Performance Green micro-LEDs

3. Optical devices

Xiaodong Wang[1]
Wei Yan[1], Xinwei Wang[1], Junxi Wang[1], Ning Zhang[1]
[1] Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

Abstract text: Nowadays achieving high-performance green-emitting micro-LEDs (>500 nm) remains challenging. The notorious "green gap"—characterized by a sharp drop in internal quantum efficiency (IQE) at longer wavelengths—stems from: 1) lattice mismatch-induced dislocation defects that promote nonradiative recombination, and 2) the quantum-confined Stark effect (QCSE) caused by strain-induced piezoelectric fields in InGaN/GaN multiple quantum wells (MQWs). These issues are exacerbated in micro-LEDs, where high current densities and stringent requirements for wavelength uniformity demand defect-free active regions and suppressed efficiency droop.

While quantum dots (QDs) have shown promise in mitigating these challenges through enhanced carrier localization and strain relaxation, conventional QD fabrication methods, such as Stranski-Krastanov epitaxy or selective-area etching, face fundamental incompatibility with micro-LED manufacturing. Their limitations include low QD density, broad size distribution, and reliance on expensive nonpolar substrates, all of which hinder the mass production of wavelength-uniform micro-LED arrays.

To bridge this gap, we present a laser annealing strategy that simultaneously forms InGaN QDs and repairs defects within the InGaN/GaN MQWs. The QD-embedded MQWs exhibited a 9.3% increase in photoluminescence (PL) intensity at 527 nm, a 7 nm red-shift, and 7.4% higher IQE compared to the as-grown samples—achievements attributed to three mechanisms: 1) 3D carrier confinement suppressing QCSE-induced band bending, 2) strain relaxation at QD/GaN interfaces reducing piezoelectric polarization, and 3) laser-induced point defect healing lowering of nonradiative recombination centers.

Green LEDs fabricated with multiple laser-annealed quantum wells exhibit improved performance. The emission wavelength showed a 7 nm red-shift from 520 nm to 527 nm. The LED achieved an 11.9% enhancement in light output power under a current of 20mA, alongside a 48.9% reduction in efficiency drop when driven at 350 mA. Furthermore, the modified LEDs demonstrated improved operational reliability, as evidenced by a decrease in leakage current density. These collective improvements substantiate the potential of laser-annealed quantum dot structures to enhance both the performance metrics and device longevity in high-current-density micro-LED applications.

OD-Mon-P33 - GaN-on-Si Arrayed µLEDs based Optogenetic Bioprobes for Neuroregulation

3. Optical devices

Jin Lin[1]
Binru Zhou[1], Teng Zhan[1], Yiyun Zhang[1], Xiaoyan Yi[1], Junxi Wang[1], Jinmin Li[1]
[1] Research & Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences

Abstract text: GaN-on-Si Arrayed *µ*LEDs based Optogenetic Bioprobes for NeuroregulationJin Lin[1,2], Binru Zhou[1,2], Teng Zhan[1,2], Yiyun Zhang[1,2] , Xiaoyan Yi[1,2*],Junxi Wang[1,2] and Jinmin Li[1,2]

1 Research & Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

2 Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China

Abstract text

Here we report a green RCLED array biological probes based on silicon substrate and it was biologically validated in the prefrontal brain region of mice. In addition, the emission angle of RCLED device was 90°, which reduced 28% compared to conventional LED device. Due to the cavity confinement, the central emission wavelength and output optical power density of this device are more stable and higher. And the maximum temperature rise can be further suppressed to 0.4 ℃. Furthermore, the optical probe combined with optogenetic viral expression of the MAC protein can alleviate neuropathic pain in mice. We also report the results of optogenetics device using a GaN based blue Micro-LED array, which enables multi-channel, frequency-adjustable light stimulation.

OD-Mon-P34 - Size Effect Induced by Straggle Diffusion in Micro-LED Arrays for Visible Light Communication Devices

3. Optical devices

Ray Hua Horng[1]
Po-Chiao Wang[2]
[1] Institute of Electronics, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan
[2] Institute of Pioneer Semiconductor Innovation, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan

Abstract text: In recent years, the fast response time and exceptional optical performance of micro-LEDs have positioned them as promising candidates for visible light communication (VLC) applications. These devices enable high-speed data transmission with advantages such as high data rates, immunity to electromagnetic interference, and enhanced security. In this work, micro-LED arrays with varying pixel sizes were fabricated using arsenic ion implantation.

The InGaN-based blue LED epilayers were grown on a sapphire substrate via metal-organic chemical vapor deposition. Micro-LED arrays with pixel sizes of 5 μm, 8 μm, and 10 μm and a gap width of 4 μm were fabricated in 24×24, 15×15, and 12×12 configurations, respectively. In tis work Arsenic ion implantation was employed to further define the active area using energies of 10 keV, 20 keV, 30 keV, and 40 keV, with an implantation dose of 10^{14} cm^{-2} for each energy level.

From the optoelectrical properties measurements, it was found that all devices exhibited a blue shift of approximately 2.9 nm, with no significant differences among them. At low current densities, FWHM increased as pixel size decreased. However, above 25 A/cm^2, no substantial difference was observed, as FWHM is mainly influenced by quantum well quality.

During implantation, unintended adjacent regions were affected, leading to damage in the quantum wells. Due to their higher sidewall ratio, smaller pixel-size arrays experienced greater damage, a phenomenon known as the size effect. As concerning the measurement of frequency response and bandwidth, it was found that the 10 μm pixel device exhibited the best -3 dB bandwidth performance (113.34 MHz at 138.89 A/cm^2), which can be attributed to fewer defects and superior quantum well quality. These factors contribute to more efficient carrier recombination, ultimately enhancing bandwidth. The 10 μm device demonstrated the least noise at high data transmission rates, signifying more efficient carrier recombination and clearer eye diagrams.

OD-Mon-P35 - Implementing Two-Step p-Type Doping to Improve Device Performance of GaN p-i-n Avalanche Photodiodes

3. Optical devices

Alexandra Dolgashev[1]
Zhiyu Xu[2], Davide Balzerani[1], A. Nepomuk Otte[3], Theeradetch Detchprohm[1], Subhra Chowdhury[4], Dhrubes Biswas[4], **Russell Dupuis**[1]
[1] School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA
[2] School of Electrical and Computer Engineering, Georgia Institute of Technology
[3] School of Physics, Georgia Institute of Technology, Atlanta, GA, USA
[4] Magnolia Optical Technologies, Woburn, Massachusetts,USA

Abstract text: Gallium nitride (GaN) avalanche photodiodes (APDs) have the potential to be high-performance UV single-photon detectors based on their capabilities for low-noise operation, intrinsic visible-blind properties, and high-temperature stability. To create improved UV APDs with low dark currents, the *J-V* characteristics and responsivity must be optimized. In this work, the GaN PIN APD epitaxial structure was modified by employing a two-step Mg-doped *p*-layer. Devices with this structure were compared with "base structure" APDs employing a single Mg dopant concentration. The two-step APDs exhibited an improved responsivity while maintaining the same *J-V* characteristics as the base structure.

The two GaN APD structures were grown in an AIXTRON 6x2 CCS MOCVD reactor on (0001) *n*-type bulk GaN substrates. Both APD structures employed the following layers: 500nm *n*-GaN:Si with [*n*]=1e18cm^{-3}, 1000nm *n*-GaN: Si with [*n*]=6e18cm^{-3}, 510nm *uid* GaN, 300nm *p*-layer, and 20nm p^{+}-GaN:Mg with [Mg]=1e20cm^{-3}. The single step *p*-type doped APD had a 300nm *p*-GaN:Mg layer with [Mg]=2e19cm^{-3} while the two-step *p*-type doped APD employed 200nm *p*-GaN:Mg with [Mg]=2e18cm^{-3} and 100nm *p*-GaN:Mg with [Mg]=2e19cm^{-3}. After growth, the two APD wafers were etched with inductively-coupled plasma (ICP) to create mesas with 1-2 degree bevels using gray-scale lithography with a photoresist mask. Next, recessed windows were ICP etched 110nm into the top *p*-type layer. Finally, *p*-metal (Ni/Ag/Pt) and *n*-metal (Ti/Al/Ti/Au) contact metallization, device passivation with spin on glass, and bonding pads were deposited to create the devices for testing.

Several 60µm diameter mesa devices with 38 µm diameter recessed windows were tested by performing *J-V* and spectral responsivity measurements at 300K. Under dark conditions, both devices had a forward ideality factor of *n*~2 and a reverse current density of ~1 to 3e-7A/cm^2 at 90% of their breakdown voltage (BV), which was -161V for the single *p*-type doped APD and -172V for the two step *p*-type doped APD. Responsivity measurements at 0V bias of both devices showed that the two step *p*-layer improved the photoresponse by 29% with an EQE of 81± 2% at the peak wavelength ~360nm and 35% at 280nm. At 96% of BV bias, the two step *p*-layer improved responsivity by 22% at the peak wavelength ~370nm and 66% at 280nm. Further characterization of these devices will be discussed.

OD-Mon-P36* - Response to X-ray of PVT self-supported AlN radiation detector

3. Optical devices

Wei Wang[1]
Kai Su[1], Zeyang Ren[1], Jinfeng Zhang[1], Yu Fu[1], Yue Hao[1], Jincheng Zhang[1]
[1] State Key Laboratory of Wide-Bandgap Semiconductor Devices and Integrated Technology, Xidian University, Xi'an, China

Abstract text: Radiation detectors are critical for analyzing radiation's energy, intensity, and spatiotemporal distribution in nuclear energy development, medical imaging, and space exploration. Ultra-wide bandgap semiconductor aluminum nitride (AlN) is one of the typical representatives of III-V compound semiconductor materials. It has a series of advantages such as large band-gap width (6.2 eV), high relative dielectric constant (8.5), high breakdown field strength (12 MV/cm), high thermal conductivity (3.2 W/cm·K), and high resistivity (> 10^{13} Ω·cm), making it an ideal choice for detecting strong radiation in extreme environments. However, planar AlN detectors fabricated via metal organic chemical vapor deposition (MOCVD) exhibit excessively thin AlN layers, which fail to achieve sufficient energy deposition, rendering them unsuitable for radiation detection applications. Thus, developing vertical-structure AlN radiation detectors is essential to probe fast-pulse signals and high-energy radiation in extreme operating environments.
In this study, for the first time, we successfully used self-supporting AlN materials grown by physical vapor transport (PVT) to fabricate vertical Ohmic Schottky radiation detectors and tested their X-ray radiation. Leveraging AlN's wide bandgap and high breakdown field strength, At a voltage bias of ±740V, a very low dark current of < 10^{-10} A is obtained, and at 5.9773 Gy/min dose rate X-ray radiation, an SNR of more than 6000 is obtained. At an electric field of 0.5 V/μm, the detector achieved a linearity of 0.9965, a specific sensitivity of 0.5333 μC/Gy·mm³, and a response current fluctuation rate as low as 0.347%. When the electric field was increased to 1 V/μm, these metrics shifted to 0.9902, 0.5995 μC/Gy·mm³, and 0.620%, respectively, while maintaining excellent performance. It can be seen from the results that the application of AlN detector in the environment such as strong irradiation has the possibility of further development.

OD-Mon-P37* - High-Speed Self-Biased AlGaN-Based Deep UV MSM Photodetector

3. Optical devices
Balkrishna Choubey[1]
Kankat Ghosh[1]
[1] Indian Institute of Technology Jammu, Jammu-181221, India

Abstract text: In this abstract, we attempt to show the performance of a self-biased Aluminum Gallium Nitride (AlGaN)-based deep ultraviolet (UV) metal-semiconductor-metal (MSM) photodetector. The AlGaN-based deep UV photodetectors are designed to detect wavelengths below 280nm with Al composition >0.4 and have potential applications across various fields including image sensing, flame detection, and wireless communication. The grown sample consists of 3.83µm $Al_xGa_{1-x}N$ (x = 0.55-0.94) epilayer (used as a photoactive layer), 1.9µm AlN (used as buffer layer), and sapphire (used as a substrate). The Ni/Au contacts are deposited on the AlGaN photoactive epilayer using photolithography. Furthermore, a standard photoresponse measurement setup evaluates various characteristics including responsivity, detectivity, and temporal response in self-biased mode.

The photoactive AlGaN layer is characterized using the high-resolution x-ray diffraction (HRXRD) technique. The symmetric HRXRD peak of $Al_{0.55}Ga_{0.45}N$ (0002) is observed at 35.39º, with a full width at half maximum of 0.07º, indicating superior crystalline quality. Atomic force microscopy (AFM) analysis reveals an RMS surface roughness of 621pm over a 2µm×2µm area, demonstrating the smoothness of the AlGaN epilayer. As a result, the measured dark current is suppressed to 1.02pA, indicating high crystalline quality, while the photocurrent reaches 4×10^{-10}A at 0V, demonstrating a high photo-to-dark current ratio of $>10^2$. The recorded responsivity under 255 nm illumination at 0 V is 1.2 mA/W, which displays the self-biasing capability of the device. The calculated detectivity at 0V is 2.42×10^8 Jones indicating a lower noise level in the fabricated device at 0V. The measured rise and fall time of our device are 24µs and 23µs, respectively, indicating the rapid signal capture capability of our fabricated device.

Keywords- AlGaN, Deep UV, MSM, Responsivity, Self-Biased.

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OD-Mon-P38* - Unipolar Carrier Multiplication AlGaN Ultraviolet Avalanche Photodiode with Periodically Stacked Structure

3. Optical devices

Jiying Cao[1]
Dunjun Chen[1]
[1] School of Electronic Science and Engineering, Nanjing University, Nanjing, China

Abstract text: Highly sensitive avalanche photodetector has become a promising candidate for detecting extremely weak target signals. However, the impact ionization multiplication simultaneously triggered by electrons and holes will lead to large excess noise, thus significantly influencing device avalanche performance.

Herein, we propose a distinctive AlGaN-based ultraviolet avalanche photodiode with $AlN/Al_{0.2}Ga_{0.8}N$ periodically stacked multiplication region. The higher effective masses and density of states in valence band renders holes limited in the quantum-well region, where thermalization plays a dominant role during carrier transport process. On the contrary, in the atomic-scale AlN/AlGaN stacked structure with a periodic thickness of 10 nm, the electron mutualization motion is conductive to electron obtaining sufficient energy to induce impact ionization. Hence, the mechanism of unipolar carrier induced avalanche multiplication effectively reduces device noise and improving multiplication gain. Meanwhile, the high electric field intensity and tilted energy band in the AlGaN/AlN periodically stacked region significantly contribute to the carrier impact ionization. Consequently, the device achieves a superior avalanche gain of more than 10^5 at 74 V reverse bias. It is envisioned that the unipolar carrier triggering avalanche events offers a viable route to build high-performance avalanche photodetectors.

OD-Mon-P39* - GaN radiation detectors with low-gain avalanche diode structure

4. Electronic devices

Hironori Okumura[1]
Satoshi Iida[1], Shigeki Hirose[1], Kosuke Itabashi[2], Manabu Togawa[2], Masaya Miyahara[2], Tadaaki Isobe[3], Keigo Urasaki[1], Jiro Nishinaga[4], Masataka Imura[5]
[1] Institute of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
[2] High Energy Accelerator Research Organization, Tsukuba, Ibaraki, Japan
[3] The Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama, Japan
[4] Global Zero Emission Research Center, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, Japan
[5] Research Center for Functional Materials, National Institute for Materials Science, Tsukuba, Ibaraki, Japan

Abstract text: Particle defectors for high-energy physics require an operation at high-temperature and high-radiation environments for a long period. GaN is an attractive material because of its large-scale wafer and high atomic number, which can create more *e-h* pairs per particle than SiC and diamond. A low gain avalanche diode (LGAD) is useful to obtain the fast time resolution. In GaN, hole-initiated impact ionization is preferable for the high signal gain and low excess noise due to the larger impact ionization coefficient of holes. In this study, we investigated electrical characteristics of GaN devices with hole-initiated LGAD structure and the performance of alpha-particle detection.

We used a GaN homoepitaxial layer grown by MOCVD. The designed structure of the GaN LGAD has the narrow high-field gain region close to the front side. In the gain layer, an electric field accelerates the electrons, producing additional charge carriers via a collision ionization multiplication of *e-h* pairs. The depth profiles of impurities in the GaN layer were determined by SIMS. The GaN layers had the expected concentration and uniform incorporation of Si and Mg atoms. We used the alpha particles from an Americium-241 radioactive source with the energy of 5.48 MeV, which was perpendicularly put on the package within 1 cm in air.

The *C-V* characteristic of the GaN detector with an anode diameter of 200 um was measured at room temperature. The plot had an obvious step curve at a bias voltage of −24 V due to the fully depleted gain layer. The drift region is partially depleted even at −100 V. The built-in voltage is extracted to be 3.0 V. The effective donor concentration in the gain layer is estimated to be $4x10^{17}$ cm^{-3}, close to the [Si] determined by SIMS.

The *J-V* characteristic was measured from -100 V to 5 V. The apparent turn-on voltage was 3.1 V, close to the bandgap energy of GaN. The GaN detector exhibited good rectifying behavior with a forward current of 100 A/cm^2 at 5.7 V. An on/off current ratio was ~10^9. A differential specific on-resistance was 26 mOhmcm^2 at a current density of 100 A/cm^2. The ideality factor was 2 at voltages between 2.1 and 3.0 V, because of the Shockley-Read-Hall recombination current.

Single events in alpha particle irradiations were observed, indicating that the GaN device can be used as a particle detector.

ED-Mon-P1* - Microchannel Cooling for Performance Enhancement of GaN-on-Si High Electron Mobility Transistors

4. Electronic devices

Xin Feng[1]
Jiajun Zhou[1], Linhai Zhong[1], Weihang Zhang[1], Xianhe Liu[1], Hong Zhou[1], Zhihong Liu[1], Yue Hao[1], Jincheng Zhang[1]
[1] Guangzhou Wide Bandgap Semiconductor Innovation Center, Xidian University, Xi'an 71000, China

Abstract text: Wide-bandgap semiconductor devices exhibit superior performance with higher breakdown voltage and lower on-resistance compared to Si-based devices, rendering them highly competitive in the field of electric energy conversion and communication. Notably, GaN as a representative material among WBG semiconductors, has advanced to the stage of industrial realization. However, the primary challenge faced by GaN HEMT is thermal management, particularly in high-power application, which leads to a serious degradation in electrical performance and long-term reliability. Therefore, there is an urgent need for effective thermal management technology. Microchannel liquid cooling as an active thermal management method has attracted a lot of attention owing to the high convective heat transfer efficiency, which could effectively mitigate thermal accumulation from 2DEG channel and reduce the performance degradation. So it is necessary to investigate the impact factor and effectiveness of microchannel cooling for GaN HEMT. [1-3]

This study systematically investigates the thermal management of RF GaN-on-Si HEMT using microchannel liquid cooling by theoretic thermal resistance model and experimental verification. It is found that the microchannel cooling technique could achieve a remarkable 57.8-63% reduction in junction-to-ambient thermal resistance ($R_{j\text{-}a}$), with a lower value of 14.3 K/W. Moreover, the $R_{j\text{-}a}$ could be reduced to 13.5 K/W by applying a high flow rate (430 mL/min) of the coolant. Subsequently, the operating temperature of the test device could get an obvious drop with a value of 172°C at 4.32 W to 122°C at 6.3 W. Meanwhile, the gate heat flux density reached 14.95 kW/mm^2, representing a 95% improvement. The RF GaN HEMT with microchannel cooling demonstrates a high $I_{DS,\,max}$ of 481 mA/mm with 34.3% enhancement and a good g_m of 174 mS/mm, proving that the self-heating effect is hugely alleviated. Hence, this work proves the microchannel cooling as an effective thermal management strategy to eliminate the application bottleneck for GaN HEMT, providing critical insights for next-generation power electronics design.

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ED-Mon-P2* - Low-Damage Atomic Layer Etching of GaN HEMTs Using BCl3/Ar: A Comparison with Conventional ICP Etching

4. Electronic devices

Boxuan Gao[1]
Jiejie zhu[1], Mengdi LI[1], Lingjie Qin[1], Simei Huang[1], Huilin Li[1], Yuchen Qian[1], Xiaohua Ma[1]
[1] National Engineering Research Center of Wide Band-gap Semiconductor, School of Microelectronics, Xidian University, Xi'an 710071, China

Abstract text: Atomic Layer Etching (ALE) overcomes several key limitations of traditional plasma etching methods, such as reactive ion etching (RIE) and inductively coupled plasma (ICP) etching, which suffer from imprecise depth control and surface damage. These issues degrade device performance, lowering saturation current, increasing gate leakage, and reducing transconductance and electron mobility. ALE, in contrast, uses a self-limiting etching process to achieve atomic-level precision, minimizing surface defects and trap density. This results in improved GaN-based device performance, including better threshold voltage stability, gate swing, and overall reliability.

In this study, a stepwise self-limiting etching process based on BCl_3/Ar was employed, achieving high precision with minimal damage and excellent anisotropy. BCl_3 was selected as the modification gas to avoid the etching damage caused by Cl_2 during the glow discharge process. The etching was performed at 40°C with top ICP and down RF power settings of 100/15 W, gas flow rates of 100/80 sccm, and a pressure of 5 Pa, resulting in an etching rate of 0.3 nm/cycle. The root mean square (RMS) roughness of the unetched barrier layer was 0.363 nm, decreased to 0.226 nm after ALE etching, while conventional ICP etching increased the roughness to 0.756 nm.

Based on these findings, two $Al_{0.25}GaN$ high electron mobility transistors (HEMTs) were fabricated using ALE and conventional ICP etching, respectively, and their electrical performance was compared. At an etching depth of 16 nm, with device dimensions of L_g = 1 μm, L_{sd} = 10 μm, W_g = 100 μm, and a drain voltage (V_d) of 6 V, the ALE-etched device exhibited significant performance enhancements over the ICP-etched counterpart. Specifically, the maximum drain current (Idmax) and peak transconductance (G_m) increased by 117.8% and 117.2%, respectively. Moreover, the gate leakage current was reduced by three orders of magnitude, and the on-resistance decreased by 50%.Additionally, the off-state current of the ALE-etched device was three orders of magnitude lower than that of the ICP-etched device, highlighting a substantial improvement in off-state characteristics.

These results demonstrate the potential of ALE technology in enhancing the performance of GaN-based devices, providing a promising solution for high-frequency power and high-voltage switching applications.

ED-Mon-P3 - Curvilinear HEMT Designs for Improved Thermal Distribution

4. Electronic devices

Shahed Reza[1]
Thomas Buchheit[1], Ahmmad Musha[2], Md. Shahadat Akbar[2], Ahsanul Islam[2], Mazharul Islam Sikder[2], **Andrew Binder**[1]
[1] Sandia National Laboratories, Albuquerque, New Mexico, USA
[2] MetroScientific, Dhaka, Bangladesh

Abstract text: Gallium nitride (GaN) high electron mobility transistor (HEMT) devices has emerged as the top contender for high-frequency and high-power applications. However, reliability degradation due to temperature rise is still a topic of concern. In a multi-finger device, heat is dissipated in a narrow region adjacent to the drain side of the gate, and the innermost gate fingers experience the highest temperatures. One approach to mitigating this temperature rise is to increase the spacing between adjacent gates, resulting in a larger area and a reduction in power per unit area. We present a novel HEMT structure featuring super ellipse-shaped gates with minimal area penalty that are also simple to manufacture. We used the super-ellipse equation $|x/a|^m+|x/b|^n = 1$, with m =2, n = 2/3 and a = 60µm. We used b to change gate bending from 1 to 10µm. This unique super-ellipse shape ensures a smooth transition from the gate and drain feed while offering precise shape control with minimal design complexity.

Performance comparisons between a conventional 8×120 µm HEMT and our proposed super ellipse-shaped gate HEMT were conducted using COMSOL®. We used a 300 µm×300 µm die, composed of a 2 µm GaN layer on a 80 µm Silicon substrate. An input power of 10 W with 57% efficiency resulted in 4.3 W dissipated as heat. An extensive study of the design space was conducted using the model, varying unequal spacing between gates from 15 µm to 25 µm, and different gate shapes. This temperature improvement translates to a 2.6× operating life improvement, following the rule of thumb of 2× life increase per 10°C reduction in temperature. The results of the full study and optimized structures for various gate spacings and shapes will be presented at the conference, offering valuable insights for designers in selecting designs suitable for their particular application. Although this design is developed for GaN HEMTs, it can be applied to other device technologies.

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ED-Mon-P4* - Metalorganic Vapor Phase Epitaxy Grown Pseudomorphic AlN/GaN/AlN HEMTs on AlN Substrates with Breakdown Field of 2 MV/cm

4. Electronic devices

TaeGi Lee[1]
Akira Yoshikawa[1], Sho Sugiyama[1], Manabu Arai[2], Yuji Ando[2], Jun Suda[2], Hiroshi Amano[2]
[1] Asahi Kasei, Tokyo, Japan
[2] Nagoya University, Aichi, Japan

Abstract text: AlN is an attractive material for electron device applications due to its bandgap (6.0 eV) and high thermal conductivity (340 W/mK). AlN/GaN/AlN heterostructures are expected to enhance the two-dimensional electron gas (2DEG) density and increase the maximum breakdown field [1, 2]. Hickman et al. reported a maximum breakdown field of 2.0 MV/cm in pseudomorphic AlN/GaN/AlN high-electron-mobility transistors (HEMTs) grown by molecular beam epitaxy (MBE), which is twice as high as that of conventional AlGaN/GaN HEMTs (~1.0 MV/cm) [2]. While MBE enables precise control over layer thickness and composition, its scalability is limited. In contrast, metalorganic vapor phase epitaxy (MOVPE) offers superior throughput and manufacturability, making it more suitable for mass production. Previously, we successfully achieved the pseudomorphic growth of a 21 nm-thick GaN layer on AlN by MOVPE [3]. In this study, we fabricated pseudomorphic AlN/GaN/AlN HEMTs on AlN substrates grown by MOVPE and demonstrated excellent output characteristics with high breakdown voltages.

The pseudomorphic AlN (9 nm)/GaN (12 nm)/AlN epitaxial layers were grown by MOVPE on an AlN (0001) single-crystal substrate. Hall-effect measurements revealed a sheet carrier concentration of $n_S = 2.3\times10^{13}$ cm^{-2}, a electron mobility of $\mu = 528$ cm^2/Vs, and a sheet resistance of $R_S = 507$ Ω/sq. The AlN/GaN/AlN HEMTs were fabricated without surface passivation. The source and drain electrodes (V/Al/Ni/Au) were deposited after etching the AlN barrier, while Ni/Au gate electrodes were deposited directly on the AlN barrier surface. The gate length and gate-to-drain distance were both 2 μm.

The output characteristics show a on-resistance of 6.4 Ω·mm and a maximum drain current density of 0.45 A/mm. A high I_{ON}/I_{OFF} ratio of 10^6 was observed, indicating effective suppression of leakage current. From off-state breakdown measurements, the device exhibited a high breakdown voltage of 390 V and a high breakdown field of 2.0 MV/cm, despite its simple structure without surface passivation. These results demonstrate that AlN/GaN/AlN HEMTs grown on AlN substrates by MOVPE have significant potential for high-breakdown applications.

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ED-Mon-P5* - 1200 V class vertical GaN-on-GaN p-i-n diodes with two-zone step-etched junction termination extension

4. Electronic devices

Andrzej Taube[1]
Jarosław Tarenko[2], Maciej Kamiński[2], Aneta Gołębiowska[2], Oskar Sadowski[2], Justyna Wierzbicka[1], Veronica Gao Zhan[1], Anna Szerling[1], Paweł Prystawko[3], Michał Boćkowski[3], Izabella Grzegory[3]
[1] Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw, Poland
[2] Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw, Poland and Warsaw University of Technology, Institute of Microelectronics and Optoelectronics, Warsaw, Poland
[3] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: One of the key elements of vertical high-voltage GaN-based devices is a properly designed junction termination extension (JTE) structure. One of the approaches to the fabrication of JTE structures is the use of p-type epitaxial layers and their appropriate shaping in order to obtain high values of breakdown voltage. In this work we present the fabrication and characterization of 1200V-class vertical GaN p-i-n diodes with two-zone step etched JTE structures. Devices were fabricated using p-n epitaxial structure on ammonothermally grown n-GaN bulk substrate, which consisted of 20 nm p^{++}-GaN ([Mg]~2×10^{20} cm^{-3})/500 nm p+-GaN ([Mg]~1×10^{18} cm^{-3})/12 µm n-GaN:Si ($|N_D-N_A|$~8×10^{15} cm^{-3}). Ti/Al/TiN/Au and Ni/Au were used as a ohmic contact metallization for N-face GaN backside and p-GaN anode, respectively. Thick polyimide layer was used a passivation. The length of first and second JTE zone was 20µm. The thickness of each JTE zone was ~440 nm and ~220 nm. Maximum current density over 9 kA/cm^2, minimum on-state resistance below 0.1 mΩcm^2, minimum value of the ideality factor of ~1.5 and an I_{on}/I_{off} ratio over 10^{13} was achieved. A significant dependence of the breakdown voltage on the thickness of the first JTE zone was observed. For thicknesses above 200 nm, an almost linear dependence of the breakdown voltage on the thickness of the first JTE zone was observed, reaching average values of the breakdown voltage above 1600 V for a thickness of 440 nm. A non-destructive breakdown and strong electroluminescence located on the outer edge of the anode were observed suggesting avalanche multiplication as a breakdown mechanism. The average breakdown voltage value was 1633 V with a low standard deviation of 60 V. The maximum breakdown voltage was about 1725 V, which corresponds to a termination efficiency of 87% of the ideal parallel plane breakdown voltage value. The obtained results indicate that step etched JTE structures can be used in the construction of vertical GaN-based devices, offering high, non-destructive breakdown voltages with low statistical dispersion.

This work was supported by The National Centre for Research and Development under Agreement nr TECHMATSTRATEG-III/0003/2019 for project "Complete vertically integrated technological chain for vertical GaN-on-GaN power electronics: from GaN substrate to Intelligent Energy Bank".

ED-Mon-P6 - Highly crystalline HEMT with AlGaN back-barrier on GaN substrate suppressing the carrier generation between substrate and epitaxial layer

4. Electronic devices

Kazuhiro Akiyama[1]
Kuraguchi Masahiko[1], Kenichi Sugita[2], Kunio Tsuda[2], Hideki Kimura[2]
[1] Corporate Research & Development Center, Toshiba Corporation, Kawasaki, Japan
[2] Microwave Technology Development Group, Core Technology Dept. Toshiba Infrastructure Systems & Solutions Corporation, Kawasaki, Japan

Abstract text: We have been studying HEMT structures with AlGaN back barriers for RF devices to realize high voltage and high efficiency operation by carrier confinement.

We report that the crystalline of HEMT with AlGaN back barrier was dramatically improved by changing substrates from SiC to GaN. Furthermore, we successfully suppressed carrier generation due to the Si contamination at the interface between the GaN substrate and the epitaxial(epi) layer by using an AlGaN back barrier.

We investigated the MOCVD conditions for the AlGaN back barrier and fabricated HEMTs with the structure: AlGaN barrier 20nm/UID GaN 200nm/UID $Al_{0.05}Ga_{0.95}N$ back barrier 500nm on SiC and GaN substrates. Crystalline was evaluated by TEM and AFM. Threading dislocations of 2.5e9/cm^2 and RMS of 0.12 nm were observed in the HEMT on the SiC substrate, while no threading dislocation in the TEM field of view and RMS of 0.12nm were observed in the HEMT on GaN substrate. These results indicate that the dramatic improvements in crystalline can be achieved by using a GaN substrate, even for HEMTs with AlGaN back barriers.

To estimate the carrier generation due to Si contamination at the interface between the GaN substrate and the epi layer, the HEMT structures were analyzed by SIMS, CV, and Hall measurements. SIMS analysis showed Si contamination between GaN substrate and epi layers with and without AlGaN. Schottky barrier diodes were formed on HEMTs and evaluated by CV at 1MHz. In the HEMT without the AlGaN back barrier, a carrier density of about 5e17/cm^3 was observed at this interface, corresponding to the Si concentration signal. On the other hand, no carriers were observed in HEMTs with AlGaN back barrier. This indicates that AlGaN back barrier efficiently suppresses carrier generation. The HEMT with the AlGaN back barrier on the GaN substrates showed an electron mobility of 1800cm^2/Vs by Hall measurements. This high mobility value indicates that the high crystalline of the HEMT structures and the absence of parallel conduction at the interface between the GaN substrate and the AlGaN back barrier. We believe that HEMT structures with AlGaN back barriers on GaN substrates are promising for RF devices with high efficiency operation.

This paper is based on results obtained from a project, JPNP24006 subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

ED-Mon-P7 - Threshold voltage instabilities of the vertical GaN MOS FET structures with semi-insulating channel

4. Electronic devices

Roman Stoklas[1]
Stanislav Hasenöhrl[1], Dagmar Gregušová[1], Boris Hudec[1], Štefan Haščík[1], Alex Chvála[2], Alexander Šatka[2], Juraj Priesol[2], Jan Kuzmík[1]
[1] Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia
[2] Institute of Electronics and Photonocs, Slovak University of Technology, Bratislava, Slovakia

Abstract text: To increase the performance of the next-generation high-power FETs, vertical configuration with C-doped semi-insulating (SI) GaN channel was developed [1-3]. The vertical structures grown by MOCVD on conductive GaN substrates consisted a SI channel layer (1.3 μm-thick), 2.5-μm-thick Si-doped n-GaN drift layer ($N_D \sim 10^{17}$ cm^{-3}) and the top layer ($N_D \sim 10^{18}$ cm^{-3}). Depending on C concentration (between $1x10^{17}$ and $6x10^{18}$ cm^{-3}) V_{br} of FETs between 45 and 350 V were observed with the avalanche for the highest C level [3]. Structure preparation: i) MESA isolation provided by ICP RIE; ii) a 20-nm-thick Al_2O_3 layer by thermal-ALD. The temperature instability of the threshold voltage (Vth) in a vertical GaN MOS structure, due to temperature dependent trapping/detrapping at the interface or in oxide bulk, have a significant impact on the device reliability for power electronics [4]. In our case, thermally induced positive V_{th} shift could be attributed to: i) thermal hole emission from Al_2O_3/GaN interface or Al_2O_3 bulk traps, causing an increase of the voltage hysteresis [5]; ii) an increase of the gate leakage due to the change of charge injected into the oxide; iii) the mobility reduction due to increased phonon scattering, affecting both the on-state and off-state characteristics of GaN structures [6]. The reducing of the voltage ramp from 10V/s to 0.1V/s can lead to slower redistribution of charge in the channel, and to increase voltage-sweep hysteresis, especially at elevated temperature. The off-state drain current reduction of the C-doped GaN MOS vertical structures could be due to a kind of phonon-assisted compensation mechanism [7]. The presence of the C-related levels in ungated structures was described in our previous study [2, 3]. In the case of transistors, the self-compensation mechanisms could be further affected by the gate potential. This work was supported by VEGA grants no. 2/0005/22, 1/0711/23 and by the APVV Agency contract APVV-18-0054.

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ED-Mon-P8 - In-situ control during growth and processing of GaN-based vertical power devices using optical metrology

4. Electronic devices

Frank Brunner[1]
Eldad Bahat-Treidel[1], Enrico Brusaterra[1], Ralph-Stephan Unger[1], Johannes K. Zettler[2], Kolja Haberland[2], Johannes Enslin[1], Markus Weyers[1]
[1] Ferdinand-Braun-Institut (FBH)
[2] LayTec AG

Abstract text: Vertical GaN based power switching devices are particularly desirable due to their reduced die size and high current handling capability. For that the use of highly conductive GaN substrates is mandatory to minimize specific on-state resistance and to allow for thick GaN drift layers with low built-in strain. Epitaxial growth via metalorganic vapor phase epitaxy (MOVPE) ensures both a low background doping and high growth rates. However, MOVPE on native GaN substrates faces specific challenges due to the limited thermal stability of the material, possible internal lattice bow and variations of material quality.

In this contribution optical metrology is used to measure wafer temperature, substrate curvature and reflectance during MOVPE of GaN-based power device structures. Especially short wavelength reflectance (280 nm, 365 nm and 405 nm) is sensitive to surface roughness and morphology effects. Examples how to detect roughness in early stages of GaN growth will be shown. Assessment of growth rates is hampered by the fact that homoepitaxial growth without changes in refractive index does not cause interference reflectance oscillations. Nonetheless small differences in refractive index for example between GaN layers with changing doping concentrations generate low-level reflectance oscillations enabling *in-situ* analysis. Examples of reflectance signatures at the interface between differently doped layers will be presented. Variation of growth rates on bulk GaN wafers compared to sapphire-based growth can be correlated with differences in wafer temperature measured by near-UV pyrometry. Control of wafer curvature is crucial for both the on-wafer temperature uniformity during growth as well as for processability. Depending on substrate type curvature measurements show a slight increase in concave bow during growth of the GaN drift layer indicating tensile strain incorporation. The opposite bowing during cool down reveals a slightly smaller in-plane thermal expansion value of the MOVPE-grown GaN compared to the substrate.

In-situ reflectance analysis during plasma etching is used to optimize device processing. Reflectance oscillations at interfaces between GaN layers with different types of doping allow for end point detection of individual etching steps. Perspectives for connected metrology entangling growth and etching steps will be outlined.

ED-Mon-P9* - Impact of Mg doping at the p-GaN/AlGaN/GaN heterostructure interface on Performance of E-mode HEMTs

4. Electronic devices

Haodong Wang[1]
Hongwei Gao[1], Yaozong Zhong[1], Xin Chen[1], Xinyu Sun[2], Xinchen Ge[2], Xiaolu Guo[1], Gaofei Zhi[1], Qian Sun[1], Hui Yang[1]
[1] Key Laboratory of Semiconductor Display Materials and Chips, Suzhou Institute of Nano-Tech and Nano- Bionics, Chinese Academy of Sciences, Suzhou 215123, China
[2] School of Nano-Tech and Nano-Bionics, University of Science and Technology of China, Hefei 230026, China

Abstract text: p-GaN gate HEMTs are playing an increasingly significant role in the field of commercial power electronics attributable to the well-balanced combination of performance and manufacturability. Due to the incorporation process of Mg which is characterized by a very strong memory effect and out-diffusion, the rational design of the p-GaN epitaxial layer plays a pivotal role in enabling the p-GaN gate HEMTs to achieve high threshold voltage and low on-state resistance.

In this study, performance of devices with different p-GaN growth conditions has been investigated, and the distribution of Mg in p-GaN gate is shown in Fig.1(a). The Mg concentrations at the interfaces of AlGaN/GaN in Sample A and B are 1.0×10^{18} and 2.0×10^{17}, respectively. The transfer and gate current characteristics of as-fabricated devices are plotted in Fig.1(b) and (c). Device A exhibits a larger subthreshold swing and ideality factor of the gate diode, indicating a remarkable SRH recombination current component, which is attributed to non-radiative recombination centers introduced by high Mg-doping.

As illustrated in Fig.2, during the pulsed measurements under reverse gate bias, a remarkable degradation of drain current and on-state resistance has been observed in the device with high Mg-diffusion channel. It suggests that Mg doping introduces plenty of electron traps, leading to the accumulation of negative charge under reverse gate stress. As shown in Fig. 3, two electron-trap levels were extracted by temperature-dependent current-transient method and Arrhenius equation. And it was further proved by the blue luminescence in cathodoluminescence spectra which is depicted in Fig. 4.

In summary, this study provides constructive evidence for understanding the carrier transport behaviors in the gate region and can be meaningful in further improvement of the device performance and reliability by optimizing the epitaxial growth condition.

ED-Mon-P10* - Surface Refinement and Electrical Enhancement of 3D GaN fin Structures through TMAH Treatment

4. Electronic devices

Hyun-Woo Lee[1]
Hyeon-Tak Kwak[2], Jaewon Park[2], Hoe-Min Kwak[2], Sang-Mo Koo[3], Sung-Bum Bae[2], Hyung-Seok Lee[2]
[1] Electronics and Telecommunications Research Institute (ETRI), Daejeon, South Korea / Department of Electrical Material Engineering, Kwangwoon University, Seoul, South Korea
[2] Electronics and Telecommunications Research Institute (ETRI), Daejeon, South Korea
[3] Department of Electrical Material Engineering, Kwangwoon University, Seoul, South Korea

Abstract text: This study focuses on the fabrication of GaN-based Fin structures using TMAH treatment to optimize the etching process, aiming for enhanced structural and electrical performance. During the etching phase, the process conditions were meticulously adjusted to control the formation angle and surface roughness of the device structures, ensuring precise geometrical characteristics. The optimization of TMAH treatment enabled improved structural integrity, leading to a reduction in sidewall roughness in 3D Fin structures. To quantitatively assess this, line edge roughness measurements were conducted to evaluate the impact of the optimized etching conditions on the Fin sidewalls.

In addition to structural analysis, this study investigates the correlation between surface defects and the electrical performance of the fabricated devices. To achieve this, leakage current patterns were designed and analyzed to examine how the presence of surface imperfections influences the overall device characteristics. The electrical analysis provides insight into the relationship between Fin structure uniformity and leakage behavior, offering a deeper understanding of defect-induced variations in device performance.

The results of this study demonstrate that precise control over TMAH treatment conditions significantly improves the structural quality of GaN Fin devices while minimizing surface roughness and optimizing device reliability. These findings contribute to the advancement of GaN-based FinFET technologies, particularly for power electronics applications, by enhancing the manufacturability and performance of vertical GaN devices.

ED-Mon-P11* - Monolithic GaN based Envelope Tracking Power Amplifier

4. Electronic devices

Weijun Luo[1]
Xiangran Ni[1], Qingyang Dong[1], Ke Wei[1], Xinyu Liu[1]
[1] 1 Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China; 2 University of Chinese Academy of Sciences, Beijing 100190, China

Abstract text: With the rapid development of modern wireless communication system, the modulation bandwidth and peak-to-average ratio (PAPR) of RF signals are becoming higher and higher. However, the efficiency of the classical Power Amplifier (PA) is very low in the power back-off region thus leading to a very low average efficiency. Compared with other technologies, Envelop Tracking (ET) PA has advantages in higher achievable bandwidth, linearity and especially in higher efficiency in power back-off region. ET PA mainly consists of RF PA and supply modulator (SM). The drain supply voltage of the RF PA is dynamically modulated by the SM to track the envelope of the RF signal, so the RF PA operates near saturation for most of the time, thus achieving high average efficiency under high PAPR signal. This paper presents a monolithic GaN based Envelope Tracking Power Amplifier which supports 8dB PAPR and 20MHz modulation bandwidth at 2.7GHz.

The RF PA designed for ET system is realized with two 8 × 125μm GaN HEMTs to achieve exceeding 6W and a saturated power gain above 10dB at 2.7GHz. Fig. 1 shows the fabricated chip micrograph of the MMIC PA with a dimension of 2.5mm × 1.1mm . The circuit diagram and chip micrograph of the single-phase buck-converter are shown in Fig. 2. The driver stage and power stage are integrated on a single chip. Fig. 3 shows the measured power-added efficiency (PAE) vs. Pout of the RF PA at 2.7GHz with various fixed supply voltages from 10V to 28V. The PA has a PAE of 50% and output power of around 38.5dBm at 28V. However, the PAE drops to about 20% in 8dB power back-off at 30.5dBm. When the drain supply voltage changes to 12-14V, the PAE can reach to 40% at the output power of 30.5dBm. This means the theoretical maximum efficiency improvement of the ET PA can be reached to 20%.Fig. 4. shows the experimental system of ET-PA. It can be seen from Fig. 5, the GaN based ET-PA supplied by the GaN SM could obtain an output power of 30.6dBm with a total drain efficiency (DE) of 27%. Compared with the PA with fixed 28V supply voltage, the total efficiency was increased by 8% which equals to 1.79W energy saving. In the PA system, energy loss is generally dissipated in the form of heat, so the proposed GaN ET PA has a very promising advantage in improving efficiency and thermal management.

ED-Mon-P12* - Aggressive Vertical Scaling of AlN/GaN/AlGaN HEMTs-on-Si with 80 nm Thin GaN Channel Layer: Investigation of CW vs. Pulsed Performance

4. Electronic devices

Yihao Zhuang[1]
Qingyun Xie[2], Siyu Liu[1], Hanchao Li[3], Hanlin Xie[1], Geok Ing Ng[3]
[1] Energy Research Institute, Nanyang Technological University, Singapore, Republic of Singapore
[2] National GaN Technology Centre (NGTC), Agency for Science, Technology and Research (A*STAR), Singapore, Republic of Singapore
[3] School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Republic of Singapore

Abstract text: A thin GaN channel plus a back barrier (BB) would achieve effective vertical scaling for mm-wave amplification in HEMTs, but such aggressive vertical scaling may lead to BB-induced trapping. This work demonstrates high-performance AlN/GaN/AlGaN HEMTs with a thin (80 nm) GaN channel for mm-wave (30 GHz) operation and investigates trap-induced discrepancies between continuous wave (CW) and pulsed load-pull (LP).

AlN/GaN/AlGaN HEMTs-on-Si with 80 nm GaN channel and 160 nm T-gate show excellent DC characteristics ($I_{D,max}$=1.3 A/mm, R_{on}=2.99 Ω·mm, $G_{m,max}$=0.40 S/mm, DIBL=20 mV/V). The output curve shows only 3.5% current drop at V_{DS}=10 V due to self-heating. High f_t/f_{max}=76/161 GHz (deembedded) was achieved at V_{DS}=6 V. Excellent LP performance was achieved at 30 GHz and $V_{DS,Q}$=6 V, with P_{sat}=1.0(1.2) W/mm, peak PAE=33(35)%, linear gain=11.4(11.8) dB in CW (pulsed) mode.

Significant discrepancies between CW and pulsed LPs emerged at higher $V_{DS,Q}$ (>6 V), indicating that performance degradation in CW mode was primarily driven by trapping effects rather than self-heating. At 15 V, pulsed LP achieved significantly better results than CW LP (P_{sat}=3.34 *vs.* 1.36 W/mm, peak PAE=28 *vs.* 12%). The surface states were excluded from the cause, considering the minimal pulse IV gate lag (8.7%) and negligible hysteresis in DC transfer characteristics. Tri-state pulsed IV measurements, with an additional drain stress pre-pulse, revealed an increase in current collapse and R_{on} from 5 V, saturating at 30 V. This trend correlates with the expansion of the depleted channel/BB interface, where significant traps reside. With increasing V_{DS}, the depletion region extends laterally toward the drain, while its depth is limited by the channel/BB interface. Traps/defects at the channel/BB interface, which are much closer to the 2DEG channel than conventional thicker GaN channels (≥150 nm) in such heterostructures, may reduce the 2DEG density, therefore reducing the maximum current swing in CW LPs.

In conclusion, discrepancies in CW *vs.* pulsed LPs of thin channel AlN/GaN/AlGaN HEMTs-on-Si were attributed to trapping at the channel/BB interface. To mitigate it, possible epitaxial improvements (e.g., graded AlGaN BB to avoid the abrupt interface) can be explored. This study offers insights into the design of these vertically scaled heterostructures to realize high performance GaN-on-Si HEMTs.

ED-Mon-P13* - Monolithic integration of p-GaN HEMT and poly-crystalline diamond FET for Complementary FET circuit

4. Electronic devices

Jiun Oh[1]
Minji Kim[1], Hyeondong Lee[1], Joon Seop Kwak[1]
[1] Dept. of Energy Engineering, Korea Institute of Energy Technology, Naju 58330, Korea

Abstract text: The increasing demand for energy-efficient and high-performance operation in power and RF systems has driven the development of wide-bandgap (WBG) and ultra-wide-bandgap (UWBG) semiconductor technologies.[1] These materials support efficient modulation of large currents and voltages with minimal losses. Despite their superior material properties, the incorporation of WBG devices with silicon-based CMOS platforms introduces additional parasitic effects, which limits system performance.[2] Recent efforts involve monolithic integration of complementary FETs in wide-band gap platforms to mitigate interconnect losses and improvements of both device performance and energy efficiency.[3]

This work introduces a monolithic fabrication of n-channel AlGaN/GaN E-mode transistors and p-channel diamond MOSFETs co-processed to achieve a complementary device suited for advanced power applications. By introducing a SiO_2 seeding layer on the surface of AlGaN/GaN HEMT platform, a polycrystalline diamond film exhibiting 1 μm grain size was grown to allow subsequent fabrication of both n-channel and p-channel FETs. To achieve normally-off functionality, the n-channel transistor utilized a p-GaN gate E-mode HEMT configuration, whereas the p-channel device employed a partially oxygen-termination on H-diamond FET structure. Featuring a device structure of source to gate separation / gate length / gate to drain separation (5 μm / 5 μm / 7μm), the discrete n-FET device demonstrates a threshold voltage near 0.5 V, an output current of 50 mA/mm, and an on/off ratio surpassing 10^6. Employing a device structure source to gate separation / gate length / gate to drain separation (4μm / 4μm / 4μm), the discrete p-FET device demonstrates a threshold voltage near -1.2 V, an output current of 50 μA/mm, and an on/off ratio surpassing 10^5. Although both transistors exhibit operational functionality, further optimization efforts are imperative to achieve higher efficiency for full CMOS integration. In the presentation, we will explain both theoretical and experimental circumstances in more detail.

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ED-Mon-P14* - Role of epitaxial capping material on the dynamic on resistance in a Gallium Nitride on Silicon Carbide power device

4. Electronic devices

Anirudh Venugopalarao[1]
Shantveer Kanta[1], Hareesh Chandrasekar[2], Amit Bansal[1], Digbijoy N. Nath[1], Srinivasan Raghavan[1]
[1] CeNSE, Indian Institute of Science, Bangalore 560012, India
[2] AGNIT Semiconductors, Bangalore 560012, India

Abstract text: Dynamic on-state resistance (Ron), or current collapse, characterized by an increase in effective Ron during switching from the off-state to the on-state, is a recognized challenge in GaN power devices. While the influence of buffer and passivation schemes on dynamic Ron has been extensively studied, the impact of epitaxial capping materials remains less explored.

This work investigates this effect by employing epitaxy on SiC substrates to mitigate trapping effects associated with AlGaN buffers. Identical epitaxial structures, differing only in the in-situ capping material (either gallium nitride (GaN) or silicon nitride (Si_3N_x), both 3 nm thick), were grown on semi-insulating and doped SiC substrates. This approach facilitates back-gating measurements, enabling the separation of bulk and surface trapping mechanisms. Both samples featured identical devices: an ALD-deposited alumina (Al_2O_3) gate dielectric, gate and source-connected field plates and silicon dioxide (SiO_2) passivation.

Following a 60-second, 100V reverse bias stress, the Si_3N_x-capped sample exhibited a five-fold increase in dynamic Ron compared to the GaN-capped sample. We will present data detailing the effects of varying stress biases and times, along with temperature-dependent and back-gating results, to further elucidate the role of the capping material in dynamic Ron.

ED-Mon-P15 - Evaluation of Doping Concentration-Dependent Static Performance of p-GaN Gate HEMTs under Adequately Activated Conditions

4. Electronic devices

Zuoheng Jiang[1]
Keping Wu[1], Jiawei Chen[1], Yingjie Wang[1], Xuan Liu[1], Zidong Cai[1], Yanlin Wu[1], Yuhang Liu[1], Wei Zeng[1], Haolin Hu[1], Yuxi Wan[1], **David Zhou**[1]
[1] Shenzhen Pinghu laboratory,shenzhen,China

Abstract text: Growing demands for efficient power switching are accelerating the evolution of GaN-based power devices, with Schottky-type p-GaN gate HEMTs emerging as the dominant solution. To date, Magnesium (Mg) doping remains the predominant method for realizing normally-off p-GaN HEMT, which is found that doping concentration can introduce additional deep electron traps and significantly affect the device instability. Thus, the static performance of Schottky-type p-GaN gate HEMTs fabricated with varying Mg doping concentrations were investigated, while the Mg dopants are adequately activated.

The p-GaN gate HEMTs were fabricated on 6-inch GaN-on-Si wafers using a standard CMOS compatible process, with three distinct Mg doping concentration. The C_G-V_{GS} measurements reveal acceptor concentrations (N_A) of of 2.8×10^{18} cm^{-3} (normal doping, ND), 7.2×10^{17} cm^{-3} (medium doping, MD) and 2.5×10^{17} cm^{-3} (low doping, LD) in the p-GaN layers.

As the Mg doping concentration decreases from ND to LD, the threshold voltage of p-GaN HEMT shifts postively, varying about 0.06 V at 25 ℃ and 1.5 V at 150 ℃. The gate leakage current at V_{GS} of 5 V is decreased with reduced doping concentration, about 1.5× orders of magnitude at 25 ℃ and 1.8× orders of magnitude at 150 ℃. Moreover, an improvement of 2 V in gate breakdown voltage is observed with reduced Mg doping. Interestingly, OFF-state drain leakage current demonstrates non-monotonic behavior under high drain bias, with MD devices showing the lowest leakage. This phenomenon is attributed to more electron trapping in AlGaN layer with Mg doping concentration from normal doping to MD, leading to raised energy barrier under the gate region and decreased drain leakage current. If the Mg doping concentration continues to decrease, the p-GaN layer's ability to deplete the channel current diminishes, resulting in a noticeable increase of drain current.

Reducing Mg doping concentration is demonstrated as an effective approach to enhance gate reliability, but introduce complexity for high temperature operation and OFF-state leakage current, which deserve extensive research.

Reference: [1] K. J. Chen *et al.*, *IEEE Transactions on Electron Devices*, vol. 64, no. 3, 2017. [2] J. Sun *et al.*, *IEEE Electron Device Letters*, vol. 44, no. 12, 2023. [3] Y. Wang *et al.*, *IEEE Trans. Electron Devices*, vol. 66, no. 9, 2018.

ED-Mon-P16* - Normally-off recessed p-NiO gate GaN-based HEMTs fabricated using "buffer-free" AlGaN/GaN heterostructures on SiC substrates

4. Electronic devices

Justyna Wierzbicka[1]
Wojciech Hendzelek[1], Maciej Kamiński[2], Jarosław Tarenko[2], Joanna Jankowska-Śliwińska[1], Aleksandra Wójcicka[1], Oskar Sadowski[2], Aneta Gołębiowska[2], Krzysztof Urbanowski[3], Veronica Gao Zahn[1], Anna Szerling[1], Andrzej Taube[1]
[1] Łukasiewicz Research Network - Institute of Microelectronics and Photonics, Warsaw, Poland
[2] Łukasiewicz Research Network - Institute of Microelectronics and Photonics, Warsaw, Poland And Warsaw University of Technology, Institute of Microelectronics and Optoelectronics, Warsaw, Poland
[3] Łukasiewicz Research Network - Institute of Microelectronics and Photonics, Warsaw, Poland And University of Warsaw, Warsaw, Poland

Abstract text: Two approaches are commonly used to achieve a normally-off operation of GaN-based HEMTs: a p-type gate and a recess under the gate. In this work, we combined these two solutions, applying sputtered p-NiO/Ni/Au layers as a gate stack and testing various recess depths in the AlGaN barrier layer.

In the experiments, commercially available GaN (2nm)/$Al_{0.27}Ga_{0.73}N$ (20 nm)/GaN/AlN "buffer-free" heterostructure on 4H-SiC substrate was used. The fabrication of gate-wrap around transistors started with ohmic contact formation. Next, the p-NiO/Ni/Au gate stack was sputter deposited and patterned using lift-off photolithography. On some samples, recess etching was performed with recess depth of 7, 12 and 17 nm. Low-energy BCl_3/Ar plasma ICP/RIE dry etching has been used, enabling precise etching depth control with minimal damage, which was confirmed through atomic force microscopy imaging. Etching processes were carried out using Oxford Instruments PlasmaPro 100 Cobra system equipped with a laser interferometer system. We obtained an etch rate of 2.7 nm/min determined by analyzing the endpoint detection signal and confirmed by profilometer measurements. The as-fabricated devices were then annealed at 450°C to lower the gate leakage current and passivated by deposition of SiO_2 by PECVD. Finally, the contact pads were opened and thickened by deposition and patterning of Ti/Au metal layers.

The non-recessed p-NiO gate devices were characterized by high output current of > 1 A/mm and low forward gate leakage current of < 10 μA/mm at V_{GS}=7V along with negative threshold voltage of about ~ -0.7 V (extracted by linear extrapolation at the point of the maximum slope of the I_D-V_{GS} curve, or ~-2.3 V using I_{DS}=1mA/mm criterium) and low minimum subthreshold slope of ~75 mV/dec. With increasing of the recess depth up to 17 nm positive shift of the threshold voltage and normally-off operation can be obtained. The devices with recess depth of 17 nm were characterized by high threshold voltage of ~ +1.4 V (or ~ +0.2 V @ I_{DS}=1mA/mm), minimum subthreshold slope of ~80 mV/dec forward gate leakage of ~1 μA/mm and maximum output current > 0.7 A/mm at V_{GS}=7V.

This work was partially supported by the Łukasiewicz Centre under targeted grants projects GaNLiN - 1/Ł-IMiF/CŁ/2023, GaNISM-CŁ/0611/2021/DF/DW and by the statutory funds of the Łukasiewicz-IMIF.

ED-Mon-P17* - AlN/GaN HEMTs on Si with outstanding noise and power characteristics

4. Electronic devices

Gao Guangjie[1]
Liu Zhihong[1], Hao Lu[1], Xing Weichuan[2], Zhou Hong[3], Zhang Weihang[2], Zhang Jincheng[1], Hao Yue[1], **Xin Feng**[4]
[1] State Key Laboratory of Wide-Bandgap Semiconductor Devices and Integrated Technology, School of Microelectronics, Xidian University, Xi'an 710071, China; Guangzhou Institute of Technology, Xidian Un
[2] Guangzhou Institute of Technology, Xidian University, Guangzhou 510555, China
[3] State Key Laboratory of Wide-Bandgap Semiconductor Devices and Integrated Technology, School of Microelectronics, Xidian University, Xi'an 710071, China
[4] Xidian University

Abstract text: Gallium Arsenide (GaAs) and Indium Phosphide (InP) based high electron mobility transistors (HEMTs) exhibit remarkably superior noise performance, which can be largely ascribed to their relatively high electron mobility. Nevertheless, the inherent low breakdown field strengths of GaAs and InP materials restrict their utility to low - power technological applications. Gallium Nitride (GaN) is endowed with a constellation of exceptional attributes, namely high electron mobility, a rapid electron saturation velocity, and a robust breakdown electric field. GaN HEMTs are highly anticipated to concurrently attain outstanding noise performance and realize a comparatively elevated power density.

In this work AlN/GaN HEMTs with a 130-nm T-gate on a silicon substrate were fabricated. The HEMT structure as depicted in Fig. 1(a) was grown by MOCVD on high-resistivity Silicon (111) substrate. Fig. 1(b) shows the small-signal performance for a AlN/GaN HEMT at V_{DS} = 10 V and V_{GS} = -2.2 V. The HEMTs exhibited a maximum drain current $I_{DS\text{-}MAX}$ of 1.58 A/mm, a peak transconductance $G_{M\text{-}MAX}$ of 410 mS/mm, a cut-off frequency f_T of 119 GHz, and a maximum oscillation frequency f_{max} of 146 GHz. Fig. 1(c) exhibits continuous wave (CW) power characteristics of the AlN/GaN HEMT on Si at 18 GHz. At V_{DS} of 10 V, a peak PAE of 41.5% with associated P_{OUT} 1.76 W/mm was obtained. Fig. 1(d) shows the measured minimum noise figure (NF_{min}) and associated gain (G_a) as functions of frequency from 2 to 40 GHz at V_{DS} = 5 V and I_{DS} = 90 mA/mm. The 130-nm T-gate HEMT exhibited a NF_{min} value of 1.0 dB/1.4 dB with a G_a of 6.5 dB/4.2 dB at 30 GHz/40 GHz, respectively, showing great noise performance. Our devices have concurrently accomplished remarkable noise performance and exceptional power characteristics, demonstrating their high - level functionality and superiority.

Acknowledgement: The authors would like to thank the fabrication tool support from the Guangzhou Wide Bandgap Semiconductor Innovation Center.

ED-Mon-P18* - Switching Characteristics of p-GaN Schottky-gate AlGaN/GaN HEMTs: Impact of Gate Offset

4. Electronic devices
Chao Feng[1]
Junye Wu[1], Xuan Liu[1], Yuhao Wang[1], Xinying Huang[1], Danfeng Mao[1], Rongxin Du[1], Wei Zeng[1], Haolin Hu[1], **David Zhou**[1], Yuxi Wan[1]
[1] Shenzhen Pinghu Laboratory, Shenzhen, China

Abstract text: The influence of gate offset on *p*-GaN Schottky-gate AlGaN/GaN HEMTs remains a subject of ongoing research. As device scaling continues to reduce specific on-resistance ($R_{on,sp}$), researchers must carefully balance gate controllability over the channel against gate reliability constraints. In our recent study[1], how varying gate offset (L_{offset}) affects static characteristics was investigated, including threshold voltage (V_{TH}), gate leakage current, subthreshold swing (*SS*), and peak transconductance ($g_{m,max}$). However, the critical relationship between L_{offset} and switching characteristics, a paramount concern for power system designers, has yet to be comprehensively explored.

This work analyzes switching behaviors in *p*-GaN Schottky-gate AlGaN/GaN HEMTs with submicron L_{offset}. Devices with five L_{offset} (47 nm, 79 nm, 110 nm, 210 nm, 320 nm) are designed and fabricated on a CMOS-compatible platform. Consistent with prior reports, larger gate offsets exhibited: elevated V_{TH}, reduced $g_{m,max}$, indicating a progressive degradation of gate control capability. Notably, while reverse gate leakage showed negligible L_{offset} dependence, forward gate leakage demonstrated a monotonic increase with L_{offset} enlargement.

Switching characterization employs a half-bridge double-pulse test circuit with 200-nH inductive loading. Key observations include: decreasing L_{offset} accelerate rise time (t_r) from 7.3 ns to 6.5 ns and fall time (t_f) from 7.4 ns to 6.7 ns. Turn-on delay ($t_{d(on)}$) is proportional to L_{offset} from 11.9 ns to 11.2 ns. Conversely, turn-off delay ($t_{d(off)}$) increases with L_{offset} reduction from 10.9 ns to 12.5 ns. These counterintuitive trends in delay components suggest complex charge/discharge dynamics at the device capacitances, with the underlying mechanisms warranting further investigation through TCAD simulations and capacitance-voltage analysis.

Reference:

[1] C. Feng *et al.*, "Stability of V_{TH} and R_{ON} in *p*-GaN Schottky-gate AlGaN/GaN HEMTs under reverse and gate bias stress: impact of gate offset," *physica status solidi (a)*, doi: 10.1002/pssa.202401012. (*Just Accepted*)

ED-Mon-P19* - Fabrication and characterization of high power 1200 V AlGaN/GaN HEMT transistors

4. Electronic devices

Maciej Kamiński[1]
Andrzej Taube[2], Jarosław Tarenko[1], Justyna Wierzbicka[2], Oskar Sadowski[1], Wojciech Hendzelek[2], Aleksandra Wójcicka[2], Aneta Gołębiowska[1], Krzysztof Urbanowski[2], Veronica Gao Zhan[2], Ernest Brzozowski[2], Anna Szerling[2]
[1] Łukasiewicz Research Network-Institute of Microelectronics and Photonic, Al. Lotników 32/46, 02-668 Warsaw, Poland; Warsaw University of Technology, Institute of Microelectronics and Optoelectronics, ul. Koszykowa 75, 00-662 Warsaw, Poland
[2] Łukasiewicz Research Network-Institute of Microelectronics and Photonic, Al. Lotników 32/46, 02-668 Warsaw, Poland

Abstract text: GaN power transistors are a popular choice for high-performance conversion systems. There is growing interest in GaN switches in the 1200 V voltage class, including automotive and industrial applications, such as motor drives, DC-DC converters, etc. The market expects normally-off (E-mode) transistors for power applications. Among the lateral HEMTs, the p-GaN gate architecture is mature and well suited for the production of cost-effective E-mode power systems, expanding its application in 1200 V switches.

This work will present the results of the fabrication and characterization of normally-off large periphery AlGaN/GaN HEMT transistors. The pGaN (80 nm) / AlGaN (12.5 nm) / GaN-on-Si substrates with total epi stack thickness over 7 µm were used. TiN with self-alignment technology and highly selective pGaN to AlGaN plasma Cl_2/O_2 were used to gate definition. Low resistivity Ti\Al\Ti\Au based ohmic contact were fabricated. Active region of transistors was defined by mesa etching or by high energy ion implantation. The PECVD fabricated SiO_2 layer served as passivation layer. Contact pads were thickened by electroplating up to 2-3 micrometers. The total gate width was 40x1mm=40 mm and 20x1mm=20 mm. The gate length was L_G = 2 µm. The source-gate (L_{GS}) and gate-drain (L_{GD}) distance was 3 µm and 20 µm, respectively. Devices with isolation in the form of mesa and high resistive implanted area were fabricated. The influence of isolation method on leakage current was investigated. Also behaviour of transistors without field plates were compared with transistor with field plates on 100 nm and 200 nm silicon dioxide PECVD deposited layers.

Pulsed on-state characteristics reveals maximum output current over 10 A which corresponds to 275 mA/mm. On-state resistance was about 430 mΩ (17.2 Ωmm) @ V_{GS}=6V. The positive threshold voltage of about 1.75V @ I_{DS}=1mA was obtained. The 4-terminal high-voltage off-state characteristics were measured. The devices shows soft breakdown at about 1390 V, defined as the voltage for which 1 µA/mm occurred. The leakage current above 1000 V is associated with substrate leakage current through epi stack. The devices shows destructive hard breakdown at about 1490 V.

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ED-Mon-P20* - A novel p-NiO RESURF-FP Hybrid Termination boosting AlGaN/GaN HEMTs on Si to over 2000 V

4. Electronic devices

Ruiling Gong[1]
[1] 中国

Abstract text: AlGaN/GaN 高电子迁移率晶体管 （HEMT） 是下一代高功率和高频应用的有前途的候选者。然而，由于栅极边缘附近的局部电场拥挤，实现高击穿电压 （V_{BR}） 仍然是一个挑战。为了解决这个问题，我们提出了一种新型的 p-NiO 缩小表面场 （RESURF） 混合端接，该端接集成了场板 （FP） 结构，可有效调制表面电场分布并增强器件的电压阻断能力。

这项工作系统研究了 p-NiO RESURF-FP 结构对 AlGaN/GaN HEMT 中电场调制和击穿性能的影响。结果表明，RESURF-FP 结构对直流性能的影响可以忽略不计，$I_{D,\ max}$ 略有降低（从 561 mA/mm 到 552 mA/mm），R_{on} 略有增加（从 8.4 Ω·mm 到 9 Ω·mm），如图 1（c） 所示。但是，观察到 breakdown 性能的显著增强。如图 1（d） 所示，在 L_{GD} = 12 μm 时，RESURF-FP 器件的 V_{BR} 提高了 40%（从 1150 V 到 1600 V），平均击穿场强从 0.92 MV/cm 增加到 1.33 MV/cm，证实了 RESURF-FP 终端实现的有效电场调制。进一步将 L_{GD} 扩展到 20 μm 导致创纪录的超过 2 kV 的 V_{BR} [图 1（e）]。此外，功率品质因数 （PFOM） 提高了 110%（从 0.7 GW/cm² 提高到 1.5 GW/cm²），证明了拟议端接结构的有效性。值得注意的是，$R_{on,\ sp}$-V_{BR} 特性优于 GaN HEMT 在硅、蓝宝石和 SiC 衬底上的特性[图 1（f）]，突出了 p-NiO RESURF-FP 端接在高功率 GaN 应用方面的潜力。总体而言，p-NiO RESURF-FP 混合端接有效地提高了击穿电压和 PFOM，同时保持了低 Ron，sp，为高功率硅基氮化镓应用提供了有前途的解决方案。

ED-Mon-P21* - Ultralow Specific On-Resistance in p-GaN Gate HEMTs Enabled by Optimized AlN Spacer Design

4. Electronic devices
Keping Wu[1]
Jiawei Chen[1], Zuoheng Jiang[1], Zidong Cai[1], Nan Gong[1], Xuan Liu[1], Caixin Gu[1], Rongxin Du[1], Wei Zeng[1], Haolin Hu[1], **David Zhou**[1], Yuxi Wan[1]
[1] Shenzhen Pinghu laboratory, Shenzhen 518100, China

Abstract text: Gallium Nitride devices have garnered significant market attention due to their superior performance characteristics. In the development of GaN devices, one key metric is the reduction of specific on-state resistance, allowing reduced conduction losses and more devices fabrication on a single wafer. This work reports a novel and simplified approach of inserting an AlN layer into the AlGaN/GaN two-dimensional electron gas (2DEG) structure, which effectively reduces the $R_{on,sp}$.

In this work, GaN devices are fabricated by a CMOS-compatible process, incorporating an AlN spacer layer at the AlGaN/GaN interface. The insertion of the optimized AlN spacer layer reduces alloy scattering, leading to a significant improvement in carrier mobility from 1630 cm²/V·s to 2090 cm²/V·s and the drift region resistance (Rs_TLM) from 512.8 Ω/sq to 392.3 Ω/sq.

Comparative analysis of transfer characteristics in 100 V p-GaN HEMTs reveals that devices with the optimized AlN spacer exhibit a higher threshold voltage (V_{TH} = 1.17 V) compared to those without the AlN spacer (V_{TH} = 0.69 V) . This V_{TH} increase is attributed to the AlN spacer's role in slowing the turn-on process. Moreover, the specific on-resistance of the device with the optimized AlN spacer is reduced to 14.46 mΩ·mm^2, exhibiting a 7% reduction in comparison to the AlN spacer free device (15.55 mΩ·mm^2). Extensive characterization demonstrates that the AlN spacer significantly suppresses forward gate leakage current, achieving a remarkable reduction to 46 nA/mm at V_{GS} = 5 V, about two orders of magnitude lower than the devices without AlN spacer.

The p-GaN HEMTs are proved to achieve ultralow Ron,sp through the strategic implementation of the AlN spacer layer. This methology demonstrates superior overall electrical performance, establishing its potential for high-efficiency power applications.

Reference: [1] K. J. Chen *et al.*, *IEEE Transactions on Electron Devices*, vol. 64, no. 3, 2017.

ED-Mon-P22* - Investigation of electrochemical etching properties of heavily oxygen doped n-type GaN

4. Electronic devices

Sogo Yokoi[1]
Shigeyoshi Usami[1], Masayuki Imanishi[1], Tomoaki Sumi[2], Junichi Takino[2], Yoshio Okayama[2], Masafumi Yokoyama[3], Masahiko Hata[4], Atsushi Tanaka[5], Yoshio Honda[5], Hiroshi Amano[5], Mihoko Maruyama[1], Masashi Yoshimura[6], Yusuke Mori[1]
[1] Grad. Sch. of Eng., Osaka Univ.
[2] Panasonic Holdings Corp.
[3] Sumitomo Chemical Co., Ltd.
[4] Itochu Plastics Inc.
[5] IMaSS Nagoya Univ.
[6] ILE, Osaka Univ.

Abstract text: [Background] Gallium nitride (GaN) can reportedly be dissolved by electrochemical (EC) etching, rendering it promising for use in semiconductor processing. Particularly, porous GaN formed by EC etching has been studied to improve the efficiency of LEDs and the water-splitting ability of GaN photocatalysts. However, most reports on the EC etching properties of GaN pertain to the carrier concentration range of 10^{16}-10^{19} cm^{-3}, and there are few detailed reports on the relationship between the applied voltage and etching morphology for n^+-GaN concentrations exceeding 10^{19} cm^{-3}. We developed an oxide vapor-phase epitaxy (OVPE) method for growing bulk GaN crystals. OVPE-GaN exhibits high carrier concentrations exceeding 10^{20} cm^{-3}, attributable to the high concentration of oxygen due to the use of Ga_2O. Based on the observed trends in previous studies, n^+-GaN can achieve EC etching at lower voltages and higher rates than n^--GaN; consequently, n^+-GaN can be used as a sacrificial layer for processes such as selective etching. In this study, we systematically investigated the influence of heavy oxygen doping on the EC etching properties of OVPE-GaN.

[Experiment and Result] Commercially available freestanding GaN substrates with carrier concentrations of 10^{16}–10^{19} cm^{-3} and OVPE-GaN substrates with carrier concentrations of 10^{19}–10^{20} cm^{-3} were prepared. EC etching was performed on the +c plane in a 1 mol/L KOH solution with applied voltages ranging from 3 to 15 V. Subsequent observations were conducted by optical microscopy (OM) and scanning electron microscopy (SEM). No etching was observed in the sample with a carrier concentration of 1.2×10^{16} cm^{-3}, even at 15 V, while porous etching was observed in samples at concentrations of 2×10^{18}–5×10^{19} cm^{-3}. Furthermore, the etching rate increased with increasing applied voltage. Conversely, the OVPE-GaN sample with a carrier concentration of 1.3×10^{20} cm^{-3} underwent electropolishing even at 3 V, and the etch rate reached 46 μm/min at 10 V. The transition from porous etching to electropolishing with increasing carrier concentration is hypothesized to result from a thinner depletion layer at the GaN–electrolyte interface. Thus, OVPE-GaN is promising as a sacrificial layer with high EC etching selectivity in the low-applied-voltage range.

ED-Mon-P23* - Hybrid Isolation Technology for GaN-based Planar MIS-HEMT with Regrown Degenerate n-GaN Ohmic Contact

4. Electronic devices

Xinkun Zhang[1]
Quan Dai[2], Yu Zhou[1], Qingru Wang[1], Xinlu Yang[1], Xiaoning Zhan[1], Jianxun Liu[1], Qian Li[1], Qian Sun[1], Hui Yang[1]
[1] University of Science and Technology of China, Hefei, People's Republic of China
[2] Suzhou Institute of Nano-tech and Nano-Bionics Chinese Academy of Sciences, Suzhou, People's Republic of China

Abstract text: In this work, we developed a hybrid isolation technology, featured by Cl-based inductively coupled plasma mesa etching together with N ion implantation. The technology was designed to be compatible with GaN-based planar RF MIS-HEMT fabrication with regrown degenerate n-GaN (n^{++} GaN) ohmic contact targeting on low-voltage RF terminal applications, and the fabricated device shows an output power density of 0.52 W/mm @ 3.5 GHz with the drain supply voltage of 3 V.

The hybrid isolation induces an etching mesa at a much lower height of 205 nm while the conventional one is about 440 nm, demonstrating the improved flatness of the proposed hybrid isolation technology, which is helpful for the process compatibility. According to the same transmission line model method, the hybrid isolation shows 1.14×10^{-4} mA/mm leakage biased at 40 V, while the conventional one shows 1.90×10^{-5} mA/mm leakage. It is very impressive that the hybrid isolation maintains a low enough leakage current (1.14×10^{-4} to 1.62×10^{-6} mA/mm) after the passivation, while the conventional one depicts an over 200x increase (1.90×10^{-5} to 4.64×10^{-3} mA/mm) of leakage current. The leakage stability of the hybrid isolation technology indicates it's promising for the practical MIS-HEMT fabrication.

We speculate that the discrepancy originates from the lattice damage induced by N ion implantation. Before passivation, both the C-doped GaN and the implanted one are highly resistive and show excellent electrical isolation. After passivation, abundant carriers will be induced in both the C-doped GaN buffer and the implanted one. Differently, the high temperature carbon substitutional doping during the epitaxy growth of C-doped GaN buffer may lead to a much lower carrier scattering probability than the implanted one, thus contributing a lot to the increase of leakage current. As a comparison, in the implanted sample, the GaN lattice was severely damaged by N ion and thereby led to a much higher scattering probability and the degraded carrier mobility, accounting for the excellent stability of hybrid isolation technology against passivation.

ED-Mon-P24* - Giant diffusion of ohmic contact material in GaN/AlGaN stacks

4. Electronic devices

Marie-Louise Bilke[1]
Theo Siegrist[2], Jan Gärtner[1], Andreas Großer[1], Nadine Szabo[1], Thomas Mikolajick[3], Stefan Schmult[4]
[1] NaMLab gGmbH, 01187 Dresden, Germany
[2] Department of Chemical and Biomedical Engineering, FAMU-FSU College of Engineering & National High Magnetic Field Laboratory, Tallahassee, Florida 32310, USA
[3] NaMLab gGmbH, 01187 Dresden, Germany/TU Dresden, Institute of Semiconductors and Microsystems, 01187 Dresden, Germany
[4] TU Dresden, Institute of Semiconductors and Microsystems, 01187 Dresden, Germany

Abstract text: While contacting the 2DEG in GaN/AlGaN HEMT stacks grown along the GaN c-direction with Ti- or Ta-based stacks, we experience a parasitic conduction path at the substrate/regrowth interface caused by inherent silicon adhesion originating from the atmosphere before growing the HEMT stack. This parasitic path can contribute with a sheet charge of 10^{14} cm^{-2} to the overall device conductance and is detrimental for HEMT operation, since such lateral devices cannot be switched to the off-state.[1]

This counterintuitively indicates, that heavy metal atoms such as Ti and Ta from the ohmic contact stack diffuse efficiently over several hundreds of nanometers along the c-axis. This diffusion behaviour is exemplarily discussed for Ta-based ohmic contacts.

After thermal annealing, the contacts exhibit expected ohmic behavior, but - unexpectedly - even before they do. The sheet resistance changed only slightly due to the temperature treatment, increasing from 246 Ω/sq to 274 Ω/sq, while the contact resistance decreases from 98 Ω to 25 Ω. Measurements of a reference GaN/AlGaN HEMT without parasitic conduction showed no ohmic behavior before annealing. Consequently, it can be attributed to the parasitic channel rather than the 2DEG of the heterostructure.

In contrast to TEM and EDX measurements[2], SIMS data unambiguously demonstrate, that Ta is present several hundred nanometers below the sample surface after thermal annealing. Forming of the ohmic contact is still controversially discussed. It may result from diffusion along dislocations. In this case and for a representative dislocation density of 10^{7} cm^{-2}, a local Ta concentration of 10^{20} cm^{-3} would result in an average density of 10^{13} cm^{-3}, which is below the SIMS detection limit.

Our data prove that Ta-based shallow ohmic contact formation before and after thermal annealing is impossible and underlines the importance of developing a strategy to eliminate or compensate parasitics at the regrowth interface for a GaN-on-GaN technology platform.

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ED-mon-P25* - Significant improvement of breakdown voltage of Al0.86Ga0.14N Schottky barrier diodes by atomic layer etching

4. Electronic devices

Tingang Liu[1]
Zhiyuan Liu[1], Haicheng Cao[1], Zixian Jiang[1], Kexin Ren[1], Xiaohang Li[1]
[1] Advanced Semiconductor Laboratory, Electrical and Computer Engineering Program, CEMSE Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Kingdom of Saudi Arabia

Abstract text: Donor-like surface defects in Al-rich AlGaN Schottky barrier diodes (SBDs) cause high leakage currents and low breakdown voltages, limiting their performance. To overcome these issues, surface treatments such as O_2 plasma and metal-insulator-semiconductor (MIS) structures with Al_2O_3 or Ga_2O_3 have been developed to suppress leakage and improve device performance. Atomic layer etching (ALE) removes materials with atomic precision, using low ion energy (~ 10 eV) and gentle chemical treatments which was used to remove defects caused by plasma damage[1]. In this work, ALE reduces interface traps and removes native oxide, leading to a lower leakage current and 4× higher reverse breakdown voltage.

Figure (a-h) shows the epitaxy structure, X-ray diffraction (XRD) characterizations, circular transmission line measurement (CTLM), and schematic diagram of the lateral $Al_{0.86}Ga_{0.14}N$ SBDs and different fabrication processes of samples A and B. Ti/Al/Ti (20/120/80 nm) metal stack of ohmic contact was deposited on the sample surfaces following the rapid thermal annealing (RTA) process at 950°C for 90 seconds under N_2 atmosphere using the JetFirst 200C system. For Ref sample, a Schottky metal stack of Ni/Au was deposited using an e-beam evaporator. ALE treated sample underwent the ALE process for 100 cycles only on the Schottky area, followed by the same Schottky metal stack as Ref sample.

Figure (i-s) illustrates the forward and reverse characteristics at different temperatures of the two samples. Sample A exhibits a higher leakage current and reaches the current limit at 308 V. Sample B has a lower leakage current, with a hard breakdown occurring at 1205 V. Current-Electric field relations at different temperatures indicated that high field trap assisted tunneling (TAT) conduction was decreased by ALE while variable range hopping (VRH) was almost unchanged.

Transmission Electron Microscopy (TEM) images, as shown in Figures (t-u) and (v), reveal a ~5 nm defective layer filled with oxygen in the Ref sample. These defects are attributed to native oxides formed during growth and annealing effects of the ohmic metal. After ALE treatment, the interface becomes sharper and more defined, indicating improved Schottky contact quality. Figure (v) illustrates the removal process of the surface defective layer by ALE.

ED-Mon-P26* - Si implanted ohmic contacts with modulated pulse annealing for AlGaN/GaN HEMTs

4. Electronic devices

Amer Bassal[1]
Ali Koyucuoglu[1], Andreas Thies[1], Ina Ostermay[1], Pallabi Paul[1], Serguei Chevtchenko[1], Oliver Hilt[1]
[1] Ferdinand-Braun-Institut (FBH), Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany

Abstract text: Low resistance ohmic contacts can be challenging for down-scaled AlGaN/GaN HEMTs with short source-drain distances needed for Q-band applications. Commonly, rough metal surfaces and edges result from contact-metal alloying. Low temperature contacts with smoother metal surfaces and better edge definition are enabled by reducing the Schottky barrier by n^+ implantation. However, dopant activation annealing above 1000°C requires high nitrogen pressures to prevent GaN decomposition. Alternatively, pulsed RTA (PRTA) activates dopants more rapidly than decomposing GaN during pulses. A hard protection cap is then needed to prevent any decomposition by maintaining surface pressure, but such a cap often deteriorates from the high stress under PRTA and could crystalize, preventing its easy removal without damaging the heterostructure beneath.

We report on activating Si dopants implanted with a dose of $2\times10^{15}cm^{-2}$ through a modulated PRTA utilizing a stacked Al_2O_3/SiN_x annealing cap with balanced mechanical stresses during PRTA, which can be easily removed after activation. The top Al_2O_3 is also a diffusion barrier and the SiN_x underneath protects the heterostructure during cap etching and supplies it with the N environment. The wafer is pre-annealed at 900°C for out-gassing H which can promote GaN decomposition. The cap deposition starts with a 20 nm PECVD of low H-content dense SiN_x at 600°C. Then 15 nm of Al_2O_3 are grown by thermal atomic layer deposition (ALD) at 300°C. The modulated PRTA activation starts with 500°C for 5 min to out-gas H from the Al_2O_3, then 900°C for 30 s to crystallize the Al_2O_3 for added hardness, then 5 pulses peaking at 1250°C, 4 pulses at 1300°C and one at 1325°C, with 40 K/s. An activation efficiency (η) of 27% was achieved in GaN and the pulses are designed according to η vs. annealing temperature for Si in GaN. Then the Al_2O_3 was dry-etched with BCl_3, while the SiN_x can still be wet-etched with HF before depositing the Ti\Al\Ni\Au ohmic contact metal. The wafer is then passivated with SiN_x and annealed for 3 min at 650°C for contact formation, achieving a contact resistance of 1.1 Ωmm, attributed to the formation of TiN and nitrogen vacancies. Attributing to Al-Ti-N phases, further 4 min at 750°C dropped the value to 0.44 Ωmm, achieving the same value as non-implanted contacts alloyed at 890°C, but with smoother metal edges and surface.

ED-Mon-P27 - A Noval p-GaN Gate HEMT Platform with Non-Damage Dielectric Removal for GaN Comparators

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Xinyu Sun[1]
Hongwei Gao[2], Fangqing Li[1], Haoran Qie[2], Yaozong Zhong[2], Haodong Wang[1], Xin Chen[2], Xiaolu Guo[2], Xinchen Ge[2], Qian Sun[2], Hui Yang[2]
[1] School of Nano Technology and Nano Bionics, University of Science and Technology of China, Hefei 230026, China
[2] Key Laboratory of Semiconductor Display Materials and Chips, Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences (CAS), Suzhou 215123, China

Abstract text: GaN-based monolithic integration has the advantage of low parasitic effect and high process compatibility, attracting a lot of attention in achievement and optimization of its components and circuit units like inverters and comparators. This work developed a platform of p-GaN gate high-electron-mobility transistor (HEMT) with non-damage dielectric removal for the GaN-based integrated circuits, on which comparator has been demonstrated. In fabrication, high-quality low pressure chemical vapor deposition (LPCVD) SiNx was employed as the AlGaN surface passivation for both enhancement-mode HEMT (E-HEMT) and depletion-mode HEMT (D-HEMT), and also a gate dielectric for the D-HEMT. A two-step process of RIE dry etching followed by BOE wet etching was developed to remove the SiNx dielectric layer on p-GaN with its surface retaining a step-flow morphology and the roughness comparable to that of the as-grown materials. The fabricated E-HEMTs and D-HEMTs have exhibited high saturation current density and can still operate properly at 100 ºC with a slight current degradation.

Through integration of the D-mode metal-insulator-semiconductor HEMTs (MIS-HEMT) with the E-HEMTs, a voltage comparator was fabricated on the developed platform. It demonstrates a comparison range from 1 to 4 V at a supply voltage (VDD) of 5 V, and can operate well at a frequency of 200 kHz with rapid switching speed, which is evidenced by a rise time of 523 ns and a fall time of 378 ns. The comparator maintains stable performance up to 200°C, showcasing its potential for high-temperature applications. This work presents a novel platform with the p-GaN E-HEMTs fabricated with high-quality LPCVD SiNx and a stable non-damage gate dielectric removal process. Due to the high performance of both E-HEMTs and D-HEMTs, faster switching speeds can be achieved in GaN monolithically integrated drivers and peripheral auxiliary circuits, advancing the development of GaN-based ICs with applications in high-frequency and high-temperature conditions.

ED-Mon-P28* - Suppression of Mg contamination of the channel region by introduction of diffusion absorption layer under p-GaN in e-HEMT structures

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Rudolf Shymon[1]
Pavel Hubík[1], Halyna Kozak[1], Tomáš Hubáček[1], Alice Hospodková[1]
[1] Institute of Physics, CAS, Praha 6, Czech Republic

Abstract text: The incorporation of an absorption layer of undoped GaN (u-GaN) inserted between the p-GaN and the AlGaN layers is investigated as a strategy to inhibit magnesium diffusion into the channel region of p-GaN enhancement-mode high-electron mobility-transistors (e-HEMTs). Mg diffusion from the p-GaN layer can lead to degradation of the device performance, contaminating an undoped channel region adversely affecting the two-dimensional electron gas (2DEG) formation and mobility. In this study, we analyse the effectiveness of an undoped GaN absorption layer added to the structure below p-GaN layer to act as a barrier against Mg diffusion.

Secondary ion mass spectrometry (SIMS) is used to measure the doping profile and penetration depth of Mg diffusion. To study the effect of the Mg diffusion on the properties of 2DEG channel, the p-GaN suppression layer was etched allowing a direct observation of the channel. The electrical properties of the channel region are assessed using Van der Pauw (VdP) method, including carrier concentration, mobility, and sheet resistance. Obtained results are compared to the same structure grown without a p-GaN layer, uncontaminated by Mg impurities.

Experimental results demonstrate that the u-GaN layer effectively reduces Mg penetration into the channel and into AlGaN blocking layer, thus avoiding the degradation of 2DEG properties. Furthermore, doping concentration profile shows a higher accumulation of the Mg near the surface, creating a doping profile, that may adversely affect the reliability of the device. By preventing Mg contamination of the channel and AlGaN layers, the u-GaN layer helps to maintain the high performance and reliability of these devices.

ED-Mon-P29 - Characterization of MOVPE grown n-GaN for Re-Al-X-Au based ohmic contacts: Effect of barrier layer (X = Re, Mo, Ni, Ti & Pd)

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Amit P. Shah[1]
Bhagyashree A. Chalke[1], Arnab Bhattacharya[1]
[1] Tata Institute of Fundamental Research, DCMP & MS, Mumbai 400005, India

Abstract text: The effect of barrier layer metal on ohmic contacts on MOVPE grown n-GaN[1] using Re-Al-**X**-Au **(X = Re, Mo, Ni, Ti and Pd)** on the electrical and microstructural characteristics is reported. The n-GaN samples had an electron density of 7.5 x 10^{18} cm^{-3} and mobility of 180 cm^2/Vs. Several samples of (Re-Al-**X**-Au : 30-100-**60**-100 nm) with different barrier layers **X** were annealed at 550—750ºC. Electrical characteristics were obtained using C-TLM measurements. AFM, GI-XRD and SEM-EDS were used to analyze the chemical composition and microstructure of the contacts. The annealing temperatures for the lowest contact resistivity were 650-700ºC[2].

The ρ_c values obtained for Mo, Ni and Ti are <10^{-7} Ω-cm^2, while for Re and Pd, the values are ~ 10^{-6}—10^{-7} Ω-cm^2. The saturation current of the I-V measurement at 300 K gave the series resistance of the ohmic contact 4.4 Ω-mm. Field-emission seems to be the dominant transport mechanism.

AFM images (40 µm x 40 µm) of the surface morphology of Re-Al-**X**-Au ohmic contacts for barrier layers showed smooth surface morphology for Re and Mo while the Ti layer showed numerous sub-micron sized islands and the Ni layer showed larger sized islands of size 2-3 µm[3]. The Pd layer had individual islands of 1-2 µm size, accumulating in larger groups. The surface RMS roughness for Re, Mo, Ni, Ti and Pd samples were 41, 60, 137, 73 and 211 nm respectively. All the samples showed sharp edge acuity under SEM.

Cross-sectional EDS linescans through the metal stack were used to investigate the alloy compositions and potential intermixing, and showed that the top Au layer had penetrated the **X** layer towards Al to form Al-Au alloys. Single linescans for contacts with Re and Mo barriers showed uniform mixture of layers across the total area. For the samples with Ni, Ti and Pd barriers, two linescans were used, one through the agglomerate and other outside it. The barrier layers are accumulated as **Al-X** agglomerates, with no traces of **X** outside. GI-XRD showed various common phases of different metal alloys like Al-Au, Al-Re, Re-Ga, Re-N, while specific Al-alloy phases of Re, Mo, Ni, Ti and Pd were observed.

This work highlights the influence of barrier layer metals for optimizing Re-based ohmic contacts to n-GaN.

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ED-Mon-P30* - Influence of the Atomic Layer Etching sequence on the electrical behavior of gate recessed AlGaN/GaN High Electron Mobility Transistors

4. Electronic devices
Christian Miersch[1]
Sarah Seidel[1], Alexander Schmid[2], Johannes Heitmann[3], Franziska C. Beyer[1]
[1] Fraunhofer Institute of Integrated Systems & Device Technology IISB, Freiberg, Germany
[2] Institute of Applied Physics, TU Bergakademie Freiberg, Freiberg (Germany)
[3] Institute of Applied Physics, TU Bergakademie Freiberg, Freiberg (Germany); Fraunhofer Institute of Integrated Systems & Device Technology IISB, Freiberg, Germany

Abstract text: Lateral AlGaN/GaN HEMTs have a high potential due to the formation of a two-dimensional electron gas (2DEG) on the surface between the AlGaN and GaN. However, these devices are 'normally-on', which is unfavorable in electric circuits to avoid shortenings. One way to process a 'normally-off' or e-mode device is to recess etch below the gate, to bring the contact closer to the channel and shift the threshold voltage V_{th} to positive values [1]. This recess must be very precise and as damage free as possible since the partial recess depth has to be accurate in the nanometer range and the 2DEG is very sensitive to carrier scattering. Atomic layer etching (ALE) can provide both, a high controllability and low damage. The sequential two step etching consists of a Cl_2 modification step, in which the Ga-N bonding energy is lowered and in a second removal step, where the weakened bonds will be cracked and removed by a gentle Ar plasma [2]. Ideally both steps are self-limiting and are separated by a purge step. Compared to continuous etching the process time is relatively long. Gradually reducing the need for purges and switching to continuous plasma operation effectivly shortens the cycle time and reduces the process costs and increases sustainability. Five modes were developed which all show low roughness and a constant Etch Per Cycle (EPC) of around 0.2 nm/cycle, but saving up to 88% of the process time. However, for the shortest 'pulsed-bias' mode the EPC was increased and Cl contaminations were visible [3]. Especially the influence of the plasma damage on the 2DEG can be studied by the electrical performance of the HEMTs. It could be shown, that the V_{th} can be shifted linearly with the etching depth, resulting in e-mode devices at 5 nm AlGaN barrier thickness below the gate contact. The influence of the gate leakage on the recess depth, as well as the saturation current will be discussed on transfer curves and out-put characteristics of the transistors for the five different modes.

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ED-Mon-P31* - Electrical properties of electrochemically energized n-GaN

4. Electronic devices

Riku Ando[1]
Ren Morita[1], Ryuto Iura[1], Yoriko Suda[1], Li Zhaobei[1], Gaku Kamio[1], Hiroshi Fujioka[2], Narihiko Maeda[1]
[1] Tokyo University of Technology, Hachioji city Tokyo, Japan
[2] The University of Tokyo, Institute of industrial Science, Komaba Meguro-ku Tokyo, Japan

Abstract text: To meet the recent demand for developing low-speed, low-loss etching technique for GaN-based devices, we previously proposed two-step wet etching method, where n-GaN is anodized followed by wet etching [1]. Moreover, we also have reported the electrical properties of anodized n-GaN, with the future expectation that anodized GaN will become a new high-voltage device material [2-3]. In this study, we investigated the electrical properties of electrochemical energized n-GaN not only under forward bias (for anodization) but also reverse bias conditions.

The n-GaN sample structure was 280 nm n-GaN / 520 nm i-GaN / LT-Buffer / Si substrates. Electrochemical energization was applied in the electrolyte (H_2SO_4+H_3PO_4) at 4 (forward bias for anodization) and -2 V (reverse bias) for 60 min. The X-ray photoelectron spectroscopy (XPS) was performed, revealing oxidation of both energized n-GaN. Next, the Hall effect was measured for 78-473 K. The Hall mobility (μ) decreased at all temperatures. (At room temperature (RT), μ of 450 cm^2/V_s (non-energized) decreased by 12.4 and 25.8 % for the 4 and -2 V samples, respectively.) The analysis on μ revealed that the observed decrease in μ was caused by neutral impurities generated by energization. The electron concentration (n) only slightly increased under forward bias (4 V); on the other hand, n largely decreased by 4-5 orders of magnitude under reverse bias (-2 V). (At RT, n decreased from 2.28×10^{17} to 7.60×10^{12} cm^{-3} under -2 V bias.) This result suggests that the energization at -2 V leads to the formation of deep levels that capture electrons.

In summary, we investigated the electrical properties of n-GaN energized under forward and reverse conditions. The hall mobility decreased under both bias conditions, which indicates that energization generates neutral impurities. The electron concentration increased only slightly under forward bias, while it decreased by 4-5 orders of magnitude under reverse bias, which indicates that energization under reverse bias generates deep levels. Thus, the energization effect was revealed to be significantly different between the forward and reverse bias conditions.

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ED-Mon-P32 - Performance of Ohmic Contacts on AlGaN/GaN HEMTs Recessed by Direct Laser Micromachining

4. Electronic devices

Justinas Jorudas[1]
Laimis Zubauskas[2], Maxim Moscotin[1], Simonas Indrišiūnas[2], Paulius Gečys[2], Irmantas Kašalynas[1]
[1] Department of Optoelectronics, Center for Physical Sciences and Technology (FTMC), Vilnius, Lithuania
[2] Department of Laser Technologies, Center for Physical Sciences and Technology (FTMC), Vilnius, Lithuania

Abstract text: A lot of effort is spent in various pathways to reduce ohmic contact resistance for AlGaN/GaN high electron mobility transistors (HEMTs) to realize their full potential. Typical approaches include novel Au-free metallization stacks[1], rapid thermal or selective laser annealing[2], ohmic recessing with reactive ion etching[3] and etc.

In this work, we investigate performance of the ohmic contacts on AlGaN/GaN HEMTs recessed by direct laser micromachining (DLM). Such new mask-less technology can be additive by expanding usage of recessed electric contacts in semiconductor heterostructures due to reduction of the fabrication time, material consumption, and simplifying the technology[4]. We removed material with ultrashort laser pulses in such a way that the damage to the semiconductor structure and contamination with ancillary materials can be reduced in comparison to the other known methods, for example, a reactive ion etching. Electric contacts were processed of a Ti/Al/Ni/Au (30/210/40/150 nm) metal stack annealed at 830°C for 30 seconds in nitrogen ambient. Only organic contamination removal was used prior to metallization using a piranha solution H_2SO_4:H_2O_2 (3:1). Circular transmission line measurement (CTLM) method was used to compare performance of the recessed and reference CTLM arrays. We demonstrate that DLM is suitable to achieve a controlled recessing below-barrier layers resulting in good ohmic characteristics of the electric contacts.

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A lot of effort is spent in various pathways to reduce ohmic contact resistance for AlGaN/GaN high electron mobility transistors (HEMTs) to realize their full potential. Typical approaches include novel Au-free metallization stacks[1], rapid thermal or selective laser annealing[2], ohmic recessing with reactive ion etching[3] and etc.

In this work, we investigate performance of the ohmic contacts on AlGaN/GaN HEMTs recessed by

direct laser micromachining (DLM). Such new mask-less technology can be additive by expanding usage of recessed electric contacts in semiconductor heterostructures due to reduction of the fabrication time, material consumption, and simplifying the technology[4]. We removed material with ultrashort laser pulses in such a way that the damage to the semiconductor structure and contamination with ancillary materials can be reduced in comparison to the other known methods, for example, a reactive ion etching. Electric contacts were processed of a Ti/Al/Ni/Au (30/210/40/150 nm) metal stack annealed at 830°C for 30 seconds in nitrogen ambient. Only organic contamination removal was used prior to metallization using a piranha solution H_2SO_4:H_2O_2 (3:1). Circular transmission line measurement (CTLM) method was used to compare performance of the recessed and reference CTLM arrays. We demonstrate that DLM is suitable to achieve a controlled recessing below-barrier layers resulting in good ohmic characteristics of the electric contacts.

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Selected references

ED-Mon-P33 - Ohmic electrode structure for AlGaN/GaN heterostructures near electron depletion

4. Electronic devices

Sho Shirasu[1]
Ren Morita[1], Hiroshi Fujioka[2], Narihiko Maeda[1]
[1] Tokyo University of Technology, Hachioji city Tokyo, Japan
[2] The University of Tokyo, Institute of industrial Science, Komaba Meguro-ku Tokyo, Japan

Abstract text: AlGaN/GaN heterostructures near electron depletion can be useful in some cases, for example, to improve sensitivity in sensors applications. With such applications in mind, in this study, we examined the ohmic electrode structure for AlGaN/GaN heterostructure FETs with near electron depletion suitable for device applications. Furthermore, we applied the ohmic structure to an UV (ultraviolet) sensor, and confirmed its availability.

Sample structures ware a 1.5 nm GaN cap/6 nm AlGaN (Al=0.21)/2 μm GaN/Buffer/p-Si substrate. We fabricated three types of ohmic structures: (i) structure where the ohmic electrode is formed as is (0 nm etched), (ii) structure where the electrode is formed after leaving 1.5 nm of the AlGaN layer (6 nm etched), and (iii) structure where the electrode is formed after etching to 4.5 nm below the AlGaN layer (12 nm etched). The ohmic electrode was formed by annealing (850°C, 1 min.) in a nitrogen atmosphere using 20 nm Ti/80 nm Al/20 nm Ti/100 nm Au ohmic metal layers. We examined ohmic characteristics for these three structures. Linear ohmic characteristics in I-V measurements were obtained for samples (i) and (ii), although resistivity of sample (i) was much larger than sample (ii). As for sample (iii), ohmic characteristics were not obtained, and I-V characteristics were unstable. Then, we examined I-V characteristics at elevated temperatures (100, 150°C) to check ohmic behavior of sample (i) and (ii). Sample (i) showed an increase in current with increasing temperature; whereas sample (ii) showed a decrease in current with increasing temperature, which does not reflect normal temperature dependence of channel characteristics. As a conclusion, the ohmic structure of sample (ii) was found to function properly with low resistivity. Next, we applied the ohmic structure of sample (ii) to an UV sensor. As the gate of UV sensor, NiO was formed by DC sputtering. The fabricated UV sensor was confirmed to exhibit normal response to the exposure of a 365 nm UV LED light.

In summary, we investigated ohmic structures for AlGaN/GaN heterostructures that are near electron depletion and found that structures that leave a little AlGaN layer are most suitable. We also confirmed the availability of this ohmic structure to the application of an UV sensor.

ED-Mon-P34* - Electrical properties of electrochemically energized AlGaN/GaN heterostructures

4. Electronic devices

Ren Morita[1]
Riku Ando[1], Shun Fukui[1], Yoriko Suda[1], Gaku Kamio[1], Hiroshi Fujioka[2], Narihiko Maeda[1]
[1] Tokyo University of Technology, Hachioji city Tokyo, Japan
[2] The University of Tokyo, Institute of industrial Science, Komaba Meguro-ku Tokyo, Japan

Abstract text: We have investigated the electrical conduction properties of anodized GaN with a view to developing new device materials with even higher voltage resistance than GaN [1-2]. In this study, we have investigated the electrical properties of electrochemically energized AlGaN/GaN heterostructures under forward bias (for anodization) as well as reverse bias conditions with device applications in mind.

The AlGaN/GaN heterostructure sample structure was 2 nm i-GaN / 25 nm $Al_{0.25}Ga_{0.75}N$ / 1 nm AlN / 300 nm i-GaN / LT-Buffer / Si substrates. Electrochemical energization was applied in the electrolyte (H_2SO_4+H_3PO_4) at 2, 4 V (forward bias for anodization) and -1 V (reverse bias) for 60 min. The X-ray photoelectron spectroscopy (XPS) was performed, revealing oxidation of both energized AlGaN. Next, the Hall effect was measured for 78-473 K. The Hall mobility (μ) decreased at all temperatures. (At room temperature (RT), μ of 1740 cm^2/V_s (non-energized) decreased by 91.9, 81.6 and 59.1 % for the 2, 4 and -1 V samples, respectively.) The analysis on μ revealed that the observed decrease in μ was caused by ionized and neutral impurities generated by energization. The electron concentration (n) was not observed to be temperature dependent in all AlGaN/GaN heterostructure samples. (At RT, the rate of change in n for all samples was within approximately 10% of the n of the non-energized sample of 9.65×10^{12} cm^{-2}) As will be reported by R.Ando et. al. ICNS15, the n of n-GaN decreased by 4 to 5 orders of magnitude under reverse bias. This result is completely different from the n at the AlGaN/GaN heterostructure in this study. This suggests that no deep levels are formed in the heterostructure even under reverse bias conditions.

In summary, we have investigated the electrical properties of electrochemically energized AlGaN/GaN heterostructures under forward and reverse conditions. The Hall mobility decreased under all bias conditions as the results of generation of ionized and neutral impurities by energization, whereas the electron concentration remained nearly constant. This study suggests that it may be possible to control the conductivity of semiconductors using low-cost electrochemical techniques rather than commonly used methods such as ion implantation.

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ED-Mon-P35* - Influence of GaN cap layers on the ohmic contact formation to AlScN/GaN heterostructures

4. Electronic devices

Isabel Streicher[1]
Giuseppe Greco[1], Teresa Duarte[2], Lutz Kirste[2], Patrik Straňák[2], Salvatore Di Franco[1], Valerio Votadoro[1], Filippo Giannazzo[1], Stefano Leone[2], Fabrizio Roccaforte[1]
[1] CNR-IMM, Catania, Italy
[2] Fraunhofer IAF, Freiburg, Germany

Abstract text: Energy savings in data transmission and electricity conversion are key for a more sustainable society. AlGaN/GaN high-electron mobility transistors allow for high switching frequencies, high breakdown voltages, and are capable of handling high current densities [1]. The performance of such devices can be increased by using AlScN barrier layers, which provide a larger 2DEG sheet charge carrier density [2].

The high bandgap of AlScN makes the formation of ohmic contacts on AlScN/GaN heterostructures a challenge. Direct deposition of metal stacks requires high-temperature annealing, which increase the contact resistance R_c of partially recessed, uncapped AlScN/GaN heterostructures [3]. The degradation of its surface by oxidation represents an additional challenge.

In this work, GaN cap layers are implemented to protect the AlScN from oxidation. GaN growth on AlScN by metal-organic chemical vapour deposition is challenging [4], and their quality depends strongly on the employed growth conditions.

Two approaches to ohmic contact formation without exposing the AlScN barrier to oxidation are presented: Firstly, a Ti/Al/Ni/Au metal stack is deposited directly on the GaN cap and, secondly, the cap and barrier are recessed, and the metal is deposited on the channel layer. Different generations of GaN caps were tested to evaluate the effect of their structural quality on the contact formation.

Ohmic behaviour is obtained at moderate annealing temperature (600°C). The specific contact resistance ρ_c decreases from 4.47×10^{-4} Ohm cm^2 to 4.78×10^{-5} Ohm cm^2 when the barrier is recessed. Structural and chemical analysis of the contacts (e.g. XRD, SIMS and TEM) are correlated with the electrical data from temperature-dependent TLM measurements. The predominant conduction mechanisms are determined. An increase of the annealing temperature up to 900°C leads to segregation of Sc towards the surface of the metal contacts.

The ability to form ohmic contacts at a moderate anneal temperature of 600°C allows for avoiding thermally induced degradation and paves the way for high-performing devices.

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ED-Mon-P36* - Strain engineering of silicon nitride layers for pinch-off voltage modulation of GaN high-electron-mobility transistors

4. Electronic devices

Ali Koyucuoglu[1]
Serguei Chevtchenko[1], Oliver Hilt[1], Olaf Krüger[1], Ina Ostermay[1]
[1] Ferdinand-Braun-Institut, Berlin, Germany

Abstract text: The demand for AlGaN/GaN high-electron-mobility transistors (HEMT) for system applications in 5G mobile communications has grown rapidly in recent years. However, their natural negative threshold voltage V_{th} behavior limits system integration and efficiency for several applications. Various techniques have been introduced to achieve control over the operation voltage, but each method shows several drawbacks like drain current reduction, increased dispersion or reliability issues.

An alternative approach, first introduced at FBH, takes advantage of the piezoelectric behavior of GaN and AlGaN [1]. By applying an external mechanical stress to the AlGaN barrier, the density of the two-dimensional electron gas (2DEG) can be influenced. The stress transfers to the underlying AlGaN/GaN at discontinuities in the stressed passivation film, such as steps or gate trenches, resulting in a threshold voltage shift.

For our current research, we used a new plasma-enhanced deposition system that enables the deposition of strained silicon nitride at temperatures of 600 °C. For the present work, such thermally stable and strained layers (1.7 GPa compressive strain) were implemented in GaN HEMTs. Due to the high deposition temperature, stress relaxation mechanisms are successfully suppressed. A shift of the threshold voltage by + 1.3 V, from an initial -1.7 V to -0.4 V is demonstrated. Besides the threshold voltage modulation, our devices with 150 nm gate length exhibit maximum drain current densities of more than 1 A/mm, similar absolute gate-source leakage currents of smaller than 2.3×10^{-5} A/mm, and an increased maximum transconductance from 476 mS/mm for unstrained GaN HEMTs to 588 mS/mm for HEMTs with strained SiN_x layers. Further, we observed a decrease in drain, gate, and total lag, which suggests improved high-frequency performance. These results highlight the potential of strain-engineered GaN HEMTs to effectively modulate pinch-off voltage, improving device control and performance without compromising electrical performance.

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ED-Mon-P37* - Effects of Oxygen Plasma and Hydrochloric acid surface treatment on Pseudo-Vertical GaN-on-Si Schottky diodes grown by localized epitaxy

4. Electronic devices

David Plaza Arguello[1]
Mohammed El Amrami[1], Eugénie Martinez[1], Hala El Rammouz[1], Thomas Kaltsounis[1], Matthieu Lafossas[1], Simona Torrengo[1], Julien Buckley[1], Matthew Charles[1]
[1] CEA Leti, Université Grenoble Alpes, Grenoble, France

Abstract text: Gallium Nitride (GaN) has drawn significant interest in power electronics due to its exceptional electron mobility, high saturation velocity, and critical electric field. However, limited availability and high cost of free-standing (FS) GaN substrates hinder adoption. Silicon is a cost-effective alternative substrate, but lattice and thermal coefficient mismatch with GaN generate dislocations and large tensile strain in GaN layers. Achieving the full potential of GaN on silicon requires both successful epitaxial growth and improved device processing.

This study focuses on controlling the metal-semiconductor interface on vertical GaN-on-Si devices to optimize Schottky barrier characteristics, minimizing leakage, and improving reliability. Surface treatment is key to achieving this by removing oxides and reducing defects, which directly impact electrical performance.

In this work, localised growth of 6 µm thick Si-doped n^-GaN (~2-3x$10^{16}$$cm^{-3}$) layers was performed by Metal Organic Vapor Phase Epitaxy (MOVPE) on 200 mm GaN on Si (111) template wafers patterned with a 50 nm Al_2O_3 mask. The wafers were diced into squares, and then pseudo vertical diodes were fabricated: a Ni/Au (50/150 nm) anode on the top surface and a Ti/Al/Ni/Au (95/200/20/265 nm) cathode on the lower part after etching the Al_2O_3 mask.

Before contact deposition, different surface treatments were applied: HCl, O_2 plasma, and a combination of both, with an untreated sample as a reference. Electrical measurements showed that both HCl and O_2 plasma improved the Schottky barrier and ideality factor, indicating a better interface. However, when combined, they degraded the Schottky characteristics, suggesting an unfavorable reaction at the metal-semiconductor interface. On the other hand, the combined treatment enhanced the cathode contact, reducing device resistance significantly.

X-ray photoelectron spectroscopy (XPS) helped analyze the metal-semiconductor interface and interpret the electrical results. While these findings highlight the role of surface preparation in device fabrication, further studies, particularly on annealing, are needed to fully understand and optimize contact performance in Schottky and ohmic contacts for vertical GaN-on-Si power devices.

ED-Mon-P38 - Suppression of n-Type Inversion in High-Dose Mg-Implanted GaN Layers via Cap-Annealing under Ultra-High Pressure

4. Electronic devices

Meguru Endo[1]
Hiroki Miyake[1], Kenta Watanabe[1], Kazuki Ikeyama[1], Shuhei Ichikawa[1], Yoshitaka Nagasato[1]
[1] MIRISE Technologies Corporation, Nisshin, Aichi 470-0111, Japan

Abstract text: Control of doping profile and realization of smooth surface in p-type regions via ion implantation (I/I) are essential to achieve GaN vertical power devices with high breakdown voltage and robustness. For fabrication of p-GaN layer with high doping concentration, it has been reported that a combination of Mg implantation and an annealing at an ultra-high pressure successfully contribute to activating p-GaN layer. However, we found that these processes resulted in the non-uniformity of surface roughness and n-type inversion at the surface, which made it difficult to fabricate ideal p-n junction and p-type ohmic contacts. In this study, we utilized AlN cap-annealing technique to suppress the n-type inversion and surface roughening of GaN with high-dose Mg implantation annealed at ultra-high pressure. We successfully demonstrate the reduction of surface roughness from 17.9 nm to 0.969 nm at I/I layer by using AlN cap.

Mg/N co-implantation was performed on GaN homoepitaxial layers grown on free-standing GaN substrates. We prepared two samples: (a) GaN layer (w/o-AlN) with a peak Mg concentration of 4×10^{19} cm^{-3}, and (b) GaN layer with AlN cap (with-AlN) with 250-nm-deep box-shaped Mg profile of 4×10^{19} cm^{-3}. After implantation, the annealing at an ultra-high pressure (1 GPa) at 1400°C was performed for 5 min. AlN layer was removed by wet etching process after the annealing process. To characterize surface roughness and carrier profile, AFM and SCM measurements were carried out, respectively.

The RMS surface roughness of (a) w/o-AlN reached maximum value of 17.9 nm. The carrier types of the implanted layer with RMS roughness below 2.00 nm were p-type, whereas that with RMS roughness over 10 nm were n-type at the surface of ~100 nm. The n-type inversion layer was formed deeper than the depth of Mg implanted profile. On the other hand, the RMS roughness for (b) with-AlN was 0.969 nm, and the n-type inversion was successfully suppressed. These results indicated that surface roughness over 10 nm after annealing at ultra-high pressure forms n-type inversion layer, and AlN cap-layer contributed to the suppressed decomposition of GaN from the surface, resulting in the suppressed surface roughness and formation of inversion layer.

ED-Mon-P39* - Gallium nitride patterning with atomic layer etching using conventional photoresist as etch mask

4. Electronic devices

Christoffer Kauppinen[1]
[1] VTT Technical Research Centre of Finland Ltd, Tietotie 3, Espoo, FI-02044 VTT, Finland

Abstract text: Atomic layer etching (ALE) enables precise self-limited etching of GaN down to one molecular layer per etch cycle. This level of control is important and beneficial in III-N based devices and especially in normally-off p-GaN gate high-electron mobility transistors (HEMTs), where the deterministic self-limited etching is crucial for normally-off HEMT behaviour with high device yield on wafer. However while most publications place great care and emphasis on the ALE properties like etch per cycle (EPC) and the synergy parameter (a figure of merit of ALE) very few publications actually show patterning of the material for which the ALE process is developed, and even fever do this with conventional photoresist and study possible problems in using ALE for pattern transfer. This work focuses on unidealities encountered in GaN ALE when conventional photoresist is used as the etch mask. The so called fencing, that is etch products being redeposited on mask sidewalls that remain after mask stripping, is studied using atomic force microscopy from metalorganic vapour phase epitaxy GaN thin films patterned by photolithography and ALE.

ED-Mon-P40* - Comparison of Thermal Resistance of E-mode AlGaN/GaN HEMT and D-mode AlGaN/GaN HEMT

4. Electronic devices

Seoyun Lee[1]
Myeongsu Chae[1], Jun-Hyeok Yim[1], Min-Keun Lee[1], Dong-Ik Oh[1], Ho-Young Cha[1], Hyungtak Kim[1]
[1] Department of Electronic and Electrical Engineering, Hongik University, Seoul, Republic of Korea

Abstract text: In this work, we analyzed thermal resistance (R_{TH}) in E-mode p-GaN gate AlGaN/GaN high electron mobility transistor (HEMT) and D-mode AlGaN/GaN HEMT under various temperature conditions. The conventional method compared the saturated drain current in DC and pulsed I-V measurements to estimate the R_{TH} [1]. While the drain current decreases in DC I-V due to self-heating effect (SHE) caused by the dissipated power (P_D), the SHE can be negligible in the pulsed I-V due to the short turn-on time.

The pulsed I-V was performed with a pulse width of 1 us (0.1% duty cycle) to minimize the SHE. The I-V output curves were measured with the V_D of 0 V to 20 V and the V_G of 7 V and -2 V in the E-mode HEMT and D-mode HEMT, respectively. We supposed that as P_D=0 W/mm, the channel temperature ($T_{channel}$) is equal to the ambient temperature (T_{amb}). T_{amb} ranged from 25 ℃ to 115 ℃ in the steps of 15 ℃. The variation of channel temperature ($\Delta T_{channel}$) by the SHE was calculated by ΔI_D ($I_{D.DC}$-$I_{D.Pulse}$), hence $T_{channel}$ was the sum of T_{amb} and $\Delta T_{channel}$. R_{TH} was calculated from the slope of the curves of $T_{channel}$ versus P_D.

The R_{TH} decreased from 10.91 °C·mm/W at 25 °C to 8.89 °C·mm/W at 115 °C in E-mode HEMT, while the R_{TH} increased in D-mode HEMT. As the ambient temperature increases, the R_{TH} in power devices generally increases due to the decreased thermal conductivity in the epitaxial layer [2]-[4]. The decrease in R_{TH} of E-mode HEMT is clearly unusual. This abnormal temperature dependence of R_{TH} is likely related to the presence of p-GaN layer, which is absent in D-mode HEMT. This finding suggests that p-GaN gate stack may have potential advantages in power devices. Further research on the temperature dependence of thermal resistance, along with investigation into the heat dissipation mechanisms of p-GaN gate AlGaN/GaN HEMT, is required.

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ED-Mon-P41 - Formation of 2D Magnesium-Intercalated Layers Enables Improved Ohmic Contacts on MBE-Grown p-GaN

4. Electronic devices

Haitao Wang[1]
Jia Wang[2], Changkai Yu[3], Takeru Kumabe[4], Debdeep Jena[5], Huili Grace Xing[6], Hiroshi Amano[7]
[1] IMaSS, Nagoya University, Nagoya, Japan
[2] IMaSS and IAR, Nagoya University, Nagoya, Japan
[3] MSE, Cornell University, Ithaca, USA
[4] GSE, Nagoya University, Nagoya, Japan; ECE, Cornell University, Ithaca, USA
[5] ECE, MSE and Kavli Institute, Cornell University, Ithaca, USA
[6] IMaSS, Nagoya University, Nagoya, Japan; ECE, MSE and Kavli Institute, Cornell University, Ithaca, USA
[7] IMaSS, IAR and GSE, Nagoya University, Nagoya, Japan; ECE and Kavli Institute, Cornell University, Ithaca, USA

Abstract text: Gallium nitride (GaN) is a leading wide-bandgap semiconductor for power and optoelectronic applications due to its high breakdown field and excellent carrier transport properties. However, achieving low-resistance ohmic contacts to p-type GaN remains challenging due to the deep Mg acceptor level (~170 meV) and Fermi-level pinning at the metal/semiconductor interface, which limit hole conduction. Various strategies, including Mg ion implantation, p^{++} InGaN contact layers, heavily doped p^{++} cap layer regrowth, and post-growth Mg annealing, have been explored to address this issue. Among these, Mg annealing is particularly attractive due to its simplicity, efficiency, and industrial feasibility.

Studies suggest that annealing forms a highly Mg-rich p^{+} surface layer (often described as a "MgGaN" alloy) through Mg diffusion into GaN. Recent microscopy has shown that Mg annealing induces 2D Mg-intercalated GaN superlattices (MiGs), where metallic Mg monolayers are inserted between GaN bilayers. These structures alter local strain and electronic properties, but their exact role in enabling ohmic behavior requires further investigation.

This study examines Mg annealing on molecular beam epitaxy (MBE)-grown p-GaN and identifies key differences compared to metal-organic chemical vapor deposition (MOCVD)-grown p-GaN in terms of optimal annealing temperature. These variations likely arise from differences in material properties and substrate-induced thermal effects. Our results reveal that optimal annealing temperatures vary between growth methods, emphasizing the need for process-specific optimization. Additionally, while increasing annealing temperature improves sheet resistance (R_{sh}), it does not always reduce specific contact resistivity (ρ_c). This behavior is attributed to 2D Mg-intercalated superlattices, which introduce compressive strain that modifies the band structure and enhances hole transport. Although extensive MiGs formation lowers R_{sh}, excessive Mg intercalation causes high surface stress, leading to roughness and cracking that degrade the metal–semiconductor interface.

To enable industrial adoption of Mg annealing for p-GaN ohmic contacts, further studies are required to optimize annealing conditions across different growth techniques and refine processing methods to simultaneously achieve low R_{sh} and low ρ_c.

ED-Mon-P42 - Low temperature activation of implanted Mg acceptors in GaN

4. Electronic devices

Max Reimer[1]
Christian Huber[1], Christian Zimmermann[1], Stefan Regensburger[1], Lukas Peters[1]
[1] Robert Bosch GmbH

Abstract text: Due to its high critical electrical field strength, gallium nitride (GaN) is considered a promising candidate for next-generation power devices. Compared to many other semiconductors, high quality epitaxial GaN layers can be deposited on a range of foreign substrates, enabling the use of low-cost substrates, such as Si or sapphire. Lateral GaN-based high-electron mobility transistors (HEMTs) are becoming commercially relevant in high-frequency applications and low- to medium-power applications. However, for high-voltage applications, e.g., for the use in traction inverters of electric vehicles, vertical power devices are superior to lateral power devices due to higher power densities and higher break-down voltages while exhibiting lower conduction losses. Vertical GaN MOSFETs with an n-type drift layer have emerged as a promising class of transistors for high-voltage automotive applications. To enable high break-down voltage so-called p-shielding areas have to be employed in GaN MOSFETs. For commercialization of GaN MOSFETs for high-voltage applications, it is most promising to utilize the implantation of Mg acceptors and subsequent annealing to form the p-shielding regions. The subsequent annealing is necessary for Mg to be incorporated as acceptor and suppress compensating defects formed during implantation. The annealing step poses a challenge because GaN tends to decompose at temperatures over 800 °C. Whereas UHPA is commonly used on an academic level, a standard furnace process is favoured from an industrial point of view. Here, we report on the formation of p-type regions in GaN formed by Mg implantation and subsequent annealing in a furnace at low pressures. We employ a capping layer deposited by LPCVD on the GaN surface as a protection during the annealing step. Further, we discuss what degree of activation of implanted Mg acceptors can be achieved utilizing different thermal budgets. Temperature-dependent Hall measurements are used to elucidate the effect of the thermal budget on activation of Mg acceptors and suppressing compensating defects. Our findings show that it is possible to achieve formation of local p-shielding areas in GaN via Mg implantation and annealing at relatively low temperatures utilizing a standard furnace process. This paves the way for realizing vertical GaN MOSFETs with high-reverse blocking capability.

ED-Mon-P43* - Enhancing Heat Dissipation in GaN-on-Diamond HEMTs through Device-First Transfer Bonding

4. Electronic devices

Shiming Li[1]
Mei Wu[1], Ling Yang[1], Bin Hou[1], Hao Lu[1], Meng Zhang[1], Xiaohua Ma[1], Yue Hao[1]
[1] Xidian University, Xi'an, China

Abstract text: In the past two decades, RF GaN HEMTs have rapidly advanced, with output power density (P_{out}) exceeding 30 W/mm. However, as the P_{out} increases, the self-heating effects of the devices become more severe. This is particularly true for multi-gate devices (gate width greater than 1 mm) used in MMICs, where the increased heat sources lead to more significant thermal accumulation. Diamond, the material with the highest thermal conductivity in nature, is considered the optimal passive cooling solution to address the thermal bottlenecks in GaN HEMTs. In this work, GaN-on-SiC HEMTs were transferred and bonded to single-crystal diamond substrate using room-temperature surface-activated bonding (SAB), resulting in GaN-on-Diamond HEMTs. We thinned the SiC substrate to 15 μm and successfully realized GaN-on-Diamond HEMTs using device-first method. The 15 μm thick supporting substrate effectively protected the heterojunction, and the electrical characteristics such as off-state leakage, threshold voltage (V_{th}), and breakdown voltage (BV) remained unchanged after transfer. Moreover, due to the ultra-thin supporting substrate and the low interface thermal resistance (TBR), the GaN-on-Diamond HEMTs demonstrated excellent heat dissipation capacity. Due to the enhanced heat dissipation capacity, the GaN-on-Diamond HEMTs exhibited outstanding RF characteristics. With an increase in the drain bias voltage (V_{DS}), the P_{out} of the GaN-on-Diamond HEMTs increased linearly up to 13.1 W/mm, with the PAE consistently exceeding 60%. This work provides an effective thermal management solution for high-power RF GaN HEMTs.

ED-Mon-P44* - Annealing up to 850 °C of Refractory Molybdenum-GaN Schottky Junctions for High Power, High-Temperature and RF Applications

4. Electronic devices

Amir AL ABDALLAH[1]
Malek Zegaoui[2], Beatriz Orfao[1], Yannick Roelens[1], Jeanne Treuttel[3], Martina Wiedner[3], Mohammed Zaknoune[1]
[1] IEMN C.N.R.S (Institut d'Electronique de Microélectronique et de Nanotechnologie), Lille, France
[2] IRCICA (Research Institute on software and hardware devices for information and Advanced communication), Lille, France
[3] LIRA (Laboratoire d'instrumentation et de recherche en astrophysique), Observatoire de Paris PSL, France

Abstract text: Schottky barrier diodes (SBDs) are highly promising for next-generation high-power sub-THz sources. In certain harsh environments, these devices must operate under extreme temperatures and high radiation levels. For space applications, THz spectroscopy instruments need devices that are capable of operating under extreme temperatures and/or high radiation levels as seen in the past missions to Venus (465 °C). The epilayer used for this study was grown by MOCVD on sapphire substrate with a 600 nm n^--GaN drift layer doped at 5×10^{16} cm^{-3}. The diode mesa was defined by a transfer technique using SiO_2 as a hard mask and an ICP Cl_2/Ar-optimized process for low damage. A combined surface treatment, consisting of BHF and in situ Ar etching, was carried out on the n^--GaN surface prior to the Mo/Pt/Au anode deposition. Molybdenum (Mo) was selected as the Schottky metal and chosen for its refractory physical properties with respect to temperature and its low work function of 4.5 eV anticipated to yield a low turn-on voltage. Platinum was used as a barrier layer to prevent interdiffusion with gold. This configuration allowed for robust SBDs with good ideality coefficient after different high annealing temperatures up to 850 °C in an N_2 ambient. The diodes exhibited a low turn on voltage V_{ON} of roughly 0.4 V across all annealing temperatures which is consistent with the low work function of Mo. The barrier height ϕ_B and the ideality factor η were extracted from the forward bias fitted trend function of the ln(I)-V plot. Values of ϕ_B were found to be 0.67, 0.57 and 0.61 eV, respectively, for the 600, 700 and 850 °C annealing treatments and the ideality factors were 1.05, 1.09 and 1.07, respectively. The barrier height extracted from the C^{-2}-V plot remained at a constant value of 0.76 eV across all annealing temperatures. The diodes exhibited an ultra-low ON resistance R_{ON} of 0.10 mΩ.cm^2. The reverse leakage current was dependent on annealing and was found to be as low as 0.1 µA at -10 V post-850 °C annealing for a 44 µm diameter anode which corresponds to a current density of 6.57 mA/cm^2. Subsequently, the 850 °C annealing showed the highest hard breakdown electric field of 118 V/µm. For GaN-on-sapphire Schottky diodes, this constitutes the highest reported destructive breakdown and the lowest dynamic resistance for a metal-SBD annealed at such high temperature.

ED-Mon-P45* - Over 360 V breakdown voltage Schottky barrier diodes based on Molybdenum-GaN contact annealed at 700 °C for DC power and high temperature applications

4. Electronic devices

Hugo Bouillaud[1]
Amir Al Abdallah[1], Beatriz Orfao[1], Yannick Roelens[1], Malek Zegaoui[2], Mohammed Zaknoune[1]
[1] Institute of Electronics, Microelectronics and Nanotechnology, CNRS, Lille, France
[2] Research Institute on software and hardware devices for information and Advanced communication, CNRS, Lille, France

Abstract text: High performance GaN power devices are increasingly in demand to meet the growing needs of consumer power supplies and the automotive industry. GaN Schottky barrier diodes (SBDs) are an excellent candidate for next-generation high-efficiency power devices. Indeed, they are known for their lower switching and reverse recovery times compared to PN diodes; however, the main challenge for SBDs is to achieve a sufficiently high breakdown voltage. In this study, we are investigating refractory metals for GaN Schottky contact in DC power applications. The goal is to fabricate devices with a high breakdown voltage that can operate under extreme temperatures. We have selected molybdenum as the refractory metal to fabricate the SBDs. The latter exhibits excellent operating characteristics after a high-temperature treatment compared to a conventional platinum or nickel-based metal/SC barrier. The epitaxial structure was grown by MOCVD on a sapphire substrate with a drift layer thickness of 5 µm, a nominal n-doping at $1x10^{16}$ cm^{-3} and a n^+ layer thickness of 750 nm with a doping density of $1x10^{19}$ cm^{-3}. The process flow consists of three steps with the following sequence: drift layer mesa etching, ohmic contact deposition and Schottky contact deposition. The first challenge was achieving deep etching of more than 5 µm for the GaN drift layer with minimal sidewall damage. Ohmic contact was made using a proven system based on Ti/Al/Ni/Au metallization, followed by an 850 °C rapid thermal annealing (RTA) process. Next, a Mo/Pt/Au Schottky contact was deposited on the GaN drift layer using an ebeam-based lift-off technique. In order to form the Schottky contact, a 700 °C post-annealing process was applied for 60 seconds using RTA. The device exhibits excellent electrical characteristics with a breakdown voltage (BV) of 363 V and a good ideality factor of 1.33, as extracted from I-V measurements. The net doping density, extracted from C-V characteristics, is close to the theoretical value with $1.41x10^{16}$ cm^{-3}. The specific on-resistance ($R_{on,sp}$) of the device is very low at 1.8 mΩ.cm². The resulting Baliga's figure of merit (BFOM) defined by $BV^2/R_{on,sp}$ is 73 $MW.cm^{-2}$. These initial results confirm the potential of Mo-GaN SBDs for DC power applications while ensuring reliable operation in high-temperature environments.

ED-Mon-P46* - Investigation of GaN MOS structures with SiO2 formed by atomic layer deposition using bis (ethyl-methyl-amino) silane and ozone

4. Electronic devices

Masanoabu Takahashi[1]
Yining Jiao[1], Masamichi Akazawa[1]
[1] Research Center for Integrated Quantum Electronics, Hokkaido University, Sapporo, Japan

Abstract text: GaN can realize highly efficient high-power devices. A MOS structure is a critical building block of a MOSFET. Recently, excellent properties of GaN MOS structures have been reported. In particular, an Al_2O_3 layer formed by atomic layer deposition (ALD) can achieve a nearly ideal GaN MOS interface. Still, SiO_2 is another material with high expectations because of its large bandgap and conduction/valence band discontinuities with GaN. We investigated the GaN MOS structure with an SiO_2 layer formed by a ALD using bis (ethyl-methyl-amino) silane (BEMAS) and ozone.

At the substrate temperature of 300 ℃, the optimization of the precursor temperature of BEMAS precursor to be 40 ℃ led to nearly stoichiometric SiO_2 composition indicated by the refractive index of 1.45 and the relative dielectric constant of 4.4. The deposition rate was as small as 0.055 nm/cycle. With these conditions, a MOS structure was formed on n-type GaN with a 20-nm-thick SiO_2. Under the bias range from –10 V to 5 V, the current density was on the order of 10^{-10} A/cm^2 or lower. In addition, the break down field was as high as 3 MV/cm. The slow deposition rate might have resulted in a strong chemical bond connection in SiO_2, resulting in an electrically excellent quality. On the other hand, capacitance–voltage (C–V) characteristics indicated a slight frequency dispersion with a hysteresis as small as 0.2 V. Although the interface state density (D_{it}) distribution derived from C–V curve by the high-low frequency method was on the order of 10^{11} cm^{-2}eV^{-1} in the range 0.15–0.45 eV below the conduction band edge for the SiO_2/GaN interface, D_{it} was relatively high compared to that of the Al_2O_3/GaN interface. Generally, uncontrolled interfacial oxide leads to interface disorder and deteriorates the interface properties. The electronegativity of Ga is smaller than that of Si and larger than that of Al. There is a possibility that the interfacial oxide thickness at the SiO_2/GaN interface was thicker than that of the Al_2O_3/GaN interface. Therefore, an insertion of an ultrathin Al_2O_3 interlayer might reduce D_{it}, which is the future work.

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ED-Mon-P47* - Effect of Ohmic Contact Characteristics on Al-rich AlGaN HEMT Performance

4. Electronic devices
Sakhone Pharkphoumy[1]
Hyun-Seop Kim[1]
[1] Kunsan National University, Gunsan, Republic of Korea

Abstract text: Al-rich AlGaN high electron mobility transistors (HEMTs) have been actively investigated as promising candidates for next-generation ultra-wide bandgap power devices. Compared to conventional AlGaN/GaN HEMTs, the higher aluminum composition in Al-rich AlGaN results in a significantly wider bandgap, enabling higher breakdown voltages and enhanced high-temperature reliability. In addition, the strong polarization-induced two-dimensional electron gas formation further supports their potential for extreme environment applications, making them well-suited for power electronics operating in harsh conditions such as space, industrial power systems, and high-temperature automotive applications.

Despite these advantages, achieving low-resistance ohmic contacts in Al-rich AlGaN HEMTs remains a major challenge. The increased bandgap due to the high Al composition results in large Schottky barriers, significantly increasing contact resistance and degrading device performance. This issue not only affects the on-state resistance but also limits the overall power conversion efficiency and switching performance. Various strategies, including metal stack optimization, regrowth techniques, and doping engineering under the contact region, have been explored to mitigate these issues. However, consistently achieving low contact resistance remains difficult due to process limitations and fundamental material constraints.

In this study, we investigated the influence of ohmic contact resistance on Al-rich AlGaN HEMT performance using Silvaco TCAD simulations. By varying doping concentrations under the contact and applying different ohmic contact resistance values, we analyzed their effects on current-voltage characteristics, on-resistance, and transconductance. The simulation results indicate that optimizing doping profiles under the contact region can significantly reduce contact resistance and enhance overall device performance. Furthermore, incorporating a gradual reduction in Al composition near the contact interface further improves ohmic characteristics by facilitating better electron transport and minimizing potential barriers at the metal-semiconductor interface.

This work highlights the critical role of ohmic contact engineering in maximizing the performance of Al-rich AlGaN HEMTs for high-voltage, high-temperature applications.

ED-Mon-P48* - Impact of Conventional and Pulsed Flow MOCVD on Al-Rich AlGaN Channel Layers for HEMTs

4. Electronic devices

Shyam Mohan[1]
Joocheol Jeong[1], Jooyong Park[1], Joonhyuk Lee[1], Jaejin Heo[1], **Okhyun Nam**[1]
[1] Convergence Center for Advanced Nano Semiconductor (CANS), Department of Nano-Semiconductor, Tech University of Korea (TU-Korea), Siheung, Gyeonggi 427-793, Republic of Korea.

Abstract text: AlGaN channel high electron mobility transistors are emerging as strong contenders for next-generation power devices due to their superior properties, such as high breakdown voltage, outstanding carrier mobility, and significant power density [1, 2]. MOCVD serves as a key technique for the precise control of composition, thickness, and doping in AlGaN layers [3, 6]. However, the epitaxial growth of AlGaN using Conventional MOCVD is often challenged by strong parasitic gas-phase reactions and the inherently low surface migration of Al adatoms, and it generally requires high growth temperatures (~1200 °C) to achieve high-quality Al-rich AlGaN layers. However, pulsed-flow MOCVD has emerged as an alternative approach, demonstrating the ability to produce Al-rich AlGaN layers with comparable or even superior crystal quality at lower temperatures [3-6]. In this study, high-quality AlGaN layers were successfully grown at relatively low temperatures with a reduced NH_3 molar flow rate using NH_3-pulsed flow MOCVD. The study investigated the effects of the TMAl/III input gas ratio, NH_3 flow duration, and NH_3 flow rate on the quality of the AlGaN layers. This research provides a comparative analysis of AlGaN channel layers based HEMTs devices, with a focus on the quality of layers grown by pulsed PMOCVD and conventional MOCVD techniques. Surface morphology studies using AFM and SEM revealed that layers grown with PMOCVD exhibited superior surface characteristics compared to those grown using conventional MOCVD. Additionally, RSM analysis showed that the AlGaN layers were grown pseudomorphically, with PMOCVD-grown $Al_{0.80}Ga_{0.20}N$ layers exhibiting 22.4% relaxation, while C-MOCVD-grown layers showed only 11.1% relaxation at similar Al content levels. The primary goal of the study was to examine the influence of deposition methods on the morphological, structural, and electrical properties of the $Al_{0.80}Ga_{0.20}N$ channel layers and their subsequent impact on the performance of HEMT devices fabricated from these layers. Electrical characterization of the resulting HEMTs assessed key parameters such as threshold voltage, current-handling capabilities, and breakdown voltages, offering insights into how the deposition method affects device performance. The findings highlight the potential of PMOCVD for optimizing HEMT structures, particularly for adavanced electronic devices.

ED-Mon-P49 - Contact Metallizations for p-GaN Gated HEMTs Operating at 800 °C

4. Electronic devices

Suzanne Mohney[1]
Chan-Wen Chan-Wen Chiu[1], Nathan Banner[1], Ajay Kumar Visvkarma[1], Juan Nicolas Jimenez Gaona[1], Yixin Xiong[1], Yi-Shuo Huang[1], Rian Guan[1], Rongming Chu[1]
[1] Pennsylvania State University

Abstract text: There is growing interest in electronics operating above 500 °C for space exploration, turbine engines, deep drilling of geothermal wells, and automobiles. Wide bandgap semiconductors enable high-temperature electronics, but achieving stable operation at 800 °C remains challenging. In this presentation, we describe a p-GaN gated HEMT operating stably for 1 hour at 800 °C with a remarkably high I_{on}/I_{off} ratio of 770 and complete pinch-off. Leakage current was kept low through the use of the p-GaN gate, and a high on-state current of 80 mA/mm was achieved. Survival of contact metallizations was also crucial. In the device, annealed Ti/$TaSi_2$ contacts to AlGaN/GaN were interconnected with $TaSi_2$/Pt. To examine thermal stability, related Ti/$TaSi_2$/Ti/Pt contacts were prepared on AlGaN/GaN with a thin GaN cap and characterized using a modified transfer length method test structure. Depending on fabrication conditions, annealed contacts had contact resistances normalized to width of 0.8–1.4 ohm-mm measured at room temperature and 1.5–3.7 ohm-mm measured at 800 °C. When held in the probe station for an hour at 800 °C under N_2, the contacts remained ohmic with contact resistances of 3.4–4.5 ohm-mm. When returned to room temperature, the contacts that were least altered by operation at 800°C still exhibited contact resistances of 1.4 ohm-mm, while others exhibited very slightly non-linear current-voltage characteristics. On p-GaN, Pd/$TaSi_2$ contacts did not exhibit linear current-voltage curves, but high operating temperatures facilitated hole transport across the Schottky barrier at the interface with p-GaN, aiding modulation of the HEMT. Materials characterization of the contact metallizations will shed light on interdiffusion and point to ways to further improve the contacts.

ED-Mon-P50 - KrF Excimer Pulsed Laser Annealing of Si Ion-implanted GaN using an AlN Protective Layer

4. Electronic devices

Takao Miyajima[1]
Haruto Hirota[1], Arihiro Nishigaki[1], Asami Sugimoto[1], Shuntarou Ono[1], Tomoya Yanagida[1], Yuzuka Minami[2], Yuko Arai[2], Yoshihiro Shimazaki[2], Masamitsu Toramaru[2], Yoshito Jin[2], Kazuyoshi Tomita[3], Daichi Imai[1]
[1] Depart. of Mat. Sci. and Eng., Meijo University, Nagoya 468-8502, Japan
[2] Device Techonology Lab., The Japan Steel Works, Ltd., Yokohama 236-0004, Japan
[3] Inst. of Mat. and Sys. for Sustainability, Nagoya University, Nagoya 468-8501, Japan

Abstract text: Recently, GaN-based vertical power devices have been attracting attention as highly efficient power conversion devices. For realize this, it is necessary to establish an ion implantation technique that controls the conductivity of local regions. However, the thermal annealing for carrier activation performed after ion implantation causes nitrogen desorption and reduces crystallinity. Therefore, thermal annealing using an AlN protective layer [1] and high-pressure thermal annealing [2] have been developed. However, in both cases, the entire sample needs to be thermally annealed at high temperatures, which causes a deterioration of device characteristics. Therefore, we have attempted pulsed laser annealing, which can heat only the required local regions in nanoseconds. We have previously shown that Mg implanted into GaN can be optically activated by pulsed laser annealing using an AlN protective layer [3]. Here, we attempted to demonstrate electrical carrier activation.

As samples, GaN:Si (2μm, [Si]=2×10^{18} cm^{-3}), and GaN:Mg (2μm, [Mg]=5×10^{17} cm^{-3}) were grown on an n-type GaN substrate by MOCVD, and Si were implanted into them. The acceleration energy was 40keV, and the dose was 3×10^{15} cm^{-2}. After ion implantation, an AlN layer was formed on the GaN surface, and the surface was irradiated with a KrF pulse laser (λ=248 nm, Δt= 28 ns). Here, we used the incident energy density P_{in} determined from the surface reflectance. The surface was evaluated using an optical and laser microscope and XPS. After removing the AlN layer, Ti/Al/Ti/Au circular electrodes were formed, and the sheet resistance and contact resistivity were determined.

When a 100-nm-thick AlN layer was used, surface ablation with a surface roughness Sa ≥ 10 nm was observed at $P_{in} \geq 300$ mJ/cm^2. On the other hand, when a 300-nm-thick AlN layer was used, Sa ≈ 3 nm at $P_{in} \leq 500$ mJ/cm^2. This indicates that the 300-nm-thick AlN layer can suppress surface ablation. Furthermore, a simulation was performed and it was calculated that the ion-implanted GaN is heated to over 1200°C by pulsed laser irradiation with P_{in} = 500 mJ/cm^2. We are currently evaluating the electrical characteristics after removing the AlN layer, and the results will be presented in the presentation.

This work was supported by MEXT-Program for INNOPEL Grant No.JPJ009777.

[1] APL **73**, 229. [2] APL **115**, 142104. [3] ICNS-13, E01.02.

ED-Mon-P51* - Highly crystalline AlN on GaN with in-situ pretreatment By Plasma Enhanced Atomic Layer Deposition

4. Electronic devices

Soumen Mazumder[1]
Safdar Muhammad[2], Varun Sharma[3], Fabien Piallat[4], Michel Khoury[5]
[1] Picosun – an Applied Materials company, Finland, Masalantie 365, FI-02430
[2] Safdar_Muhammad@amat.com
[3] Varun_Sharma@amat.com
[4] Fabien_Piallat@amat.com
[5] Michel_Khoury@amat.com

Abstract text: Gallium nitride (GaN) high-electron mobility transistors (HEMTs) have become essential
component for modern power device technology due to their excellent performance characteristics and are promising candidates for high power and radio frequency (RF) applications. However, they generally suffer from DC to RF dispersion issues, generally known as Current Collapse, which leads to significant decrease in the output power density and causes reliability related issues. Although PECVD/LPCVD SiNX is widely used as passivation material; the SiNX passivated devices suffers from high dynamic RON after high voltage stress. High quality AlN layer can effectively mitigate interface charges by generating positive fixed charges. The PEALD-AlN passivated GaN HEMTs exhibit robust current collapse suppression up to 600 V [1]. On one hand, surface states are critical sources of 2DEG in GaN HEMT, which allows very high electron concentration without doping. While on the other hand, these surface states are the main reason for DC to RF dispersion, i.e., higher current collapse. To reduce the surface states, several surface treatment techniques are available. Among those, in-situ surface treatment is preferred to obtain a pristine interface. We present results of a low temperature, non-toxic, in-situ pretreatment, followed by highly crystalline PE AlN deposition on GaN using AppliedTM MorpherTM Plasma ALD chamber.
We characterized the PE AlN crystallinity using XRD and AlN/GaN interface using TEM/EELS. The in-situ pretreatment resulted in a sharp interface between PE AlN/GaN layers, reflecting a reduction in interface defects. XRD analysis of PE AlN on GaN indicates a highly crystalline (close to epitaxial quality) growth with main direction oriented along 002 plane. The rocking curve FWHM for GaN and PE AlN is ~ 0.115 and 0.261 ° 2θ, respectively. XPS analysis indicates good stoichiometry of Al & N with low O-contamination (<at. 5%). The presented work highlights that the new AppliedTM MorpherTM Plasma ALD 200mm chamber is capable of depositing uniform, high-quality epitaxial PE AlN on GaN substrates for GaN power applications.
[1] YANG et al., Investigation of SiNx and AlN passivation for AlGaN/GaN High-ElectronMobility Transistors: Role of Interface Traps and Polarization Charges.

ED-Mon-P52* - Reduction of hole traps in GaN MOS structures by introducing Mg atoms near SiO2/GaN interfaces

4. Electronic devices

Yuichi Sakagami[1]
Masahiro Hara[1], Mikito Nozaki[1], Takuma Kobayashi[1], Heiji Watanabe[1]
[1] The University of Osaka, Suita, Osaka 565-0871, Japan

Abstract text: A GaN vertical MOSFET is a promising power device for high-voltage and high-current applications. However, numerous hole traps exist in GaN MOS structures, causing degradation of reliability of GaN MOSFETs. We have recently reported that hole traps were effectively passivated by using heavily Mg-doped GaN substrates. Moreover, decreased hole traps were reported in GaN MOS structures with an MgO as a gate insulator. Thus, it is indicated that the presence of Mg atoms near an SiO_2/GaN interface is important for decreasing hole traps. In this study, we systematically investigated the impact of a thin Mg layer deposition and annealing before SiO_2 formation on hole trap generation.

After wet cleaning of p-type GaN(0001) epilayer (~10^{17} cm^{-3}), Mg (5 or 20 nm) was deposited by vacuum evaporation. Then, N_2 or O_2 annealing was performed at 800°C for Mg diffusion into GaN bulk and/or MgO formation (labeled as Evap+N_2 or O_2 samples). After SiO_2 deposition (~20 nm) by PECVD, post-deposition annealing in O_2 ambient (O_2-PDA) was performed at 400–800°C for 30 min. Finally, Ni gate electrodes and Al back contacts were formed to fabricate MOS structures.

In the capacitance-voltage (*C-V*) characteristics of SiO_2/GaN MOS structures without an Mg interlayer, a larger hump due to severe surface potential pinning by hole traps was observed at a higher PDA temperature, and a large hysteresis was found regardless of the PDA temperature. On the other hand, all the Evap+N_2 samples exhibited hole accumulation and no hump in the *C-V* curves. However, gate leakage current was significant, and crock-wise *C-V* curves due to ion drift were observed when the O_2-PDA temperature was below 600°C. The Evap+O_2 samples also exhibited hole accumulation and no hump in the *C-V* curves without ion drift and with improved gate insulating properties. The hysteresis was reduced by increasing the Mg thickness (t_{Mg}), and nearly ideal *C-V* characteristics were obtained with t_{Mg} = 20 nm and O_2-PDA at 600°C.

This work was supported by the MEXT “Program for Creation of Innovative Core Technology for Power Electronics” (JPJ009777) and JSPS KAKENHI (25K17640).

ED-Mon-P53* - Ohmic Characteristics of n+-InAs/n+-GaAs/n+-GaN for Low-contact-resistivity Source/Drain of GaN-channel HEMTs

4. Electronic devices

Takuya Hoshi[1]
Yuki Yoshiya[1], Hiroki Sugiyama[1], Fumito Nakajima[1]
[1] NTT Device Technology Laboratories, NTT Corporation

Abstract text: To enhance the RF performance of GaN-channel HEMTs, regrowth of the low-contact-resistivity source and drain (S/D) region is essential. Although heavily n-type doped GaN is often used, its carrier concentrations are still limited. Zincblende III-V materials can be formed with very high electron concentrations of over 10^{19} cm^{-3} easily. We previously demonstrated very high carrier concentration InGaAs directly grown on GaN via a surface arsenided layer. To use these III-As layers on GaN devices, further improvement of ohmic characteristics is crucial. We investigated the process-temperature dependence and on-wafer uniformity of the ohmic characteristics of Ti/Pt/Au on III-As layers grown on both 3-inch GaN.

We first prepared n^+-InAs/n^+-GaAs layers grown on a 3-inch n^+-GaN on an Al_2O_3 template and fabricated standard TLM patterns with Ti/Pt/Au electrode. Under as-deposited condition, specific contact resistivity (ρ_c) was as high as $1x10^{-4}$ Ω*cm^2, and dispersed from 10^{-5} to 10^{-3} Ω*cm^2. This relatively high ρ_c might be due to the native oxide of InAs. After annealing at 200°C, this value decreased to ~$5x10^{-5}$ Ω*cm^2. The lowest was 2.2 $x10^{-5}$ Ω*cm^2. However, it increased again to 10^{-4} Ω*cm^2 after annealing at 300°C, indicating the stability of electrodes degraded at high-temperature annealing.

We prepared AlGaN/GaN on 3-inch S.I. 4H-SiC by MOVPE. BHF wet etching and ICP-RIE were performed to remove the SiO_2 passivation, AlGaN barrier, and a part of GaN channel of S/D region. The sample was reloaded in the MOVPE reactor and n^+-GaN was regrown. After removing the SiO_2 mask, the 2nd regrowth of n^+-InAs/n^+-GaAs was carried out. Since the surface of AlGaN is rarely arsenided, poly-crystalline n^+-InAs/n^+-GaAs was deposited on the AlGaN barrier. We used Ti/Pt/Au electrodes as S/D electrodes. After patterning the gate lithography, wet side etching of poly crystalline layers was carried out. Finally, a Ni/Au Schottky gate was deposited. The fabricated HEMT exhibited a R_{on} of 11.76 Ω*mm. The R_{on} extrapolated to $L_{S\text{-}D}$ = 0 μm was as high as 5.65 Ω*mm, which is probably due to the variation in the shape and volume of overgrown III-As polycrystalline layers crawling up on the AlGaN barrier, which should induce the non-uniformity of the electrode's contact. Therefore, precise control of the side-etching process of the polycrystalline layer is also important to lower and uniform R_{on}.

ED-Mon-P54* - Etching of vertical GaN trench structures in chlorine-based plasma: The effect of BCl_3 and $SiCl_4$ additions.

4. Electronic devices

Jarosław Tarenko[1]
Maciej Kamiński[1], Justyna Wierzbicka[2], Anna Szerling[2], Paweł Prystawko[3], Michał Boćkowski[3], Izabella Grzegory[3], Andrzej Taube[2]
[1] Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw, Poland and Warsaw University of Technology, Institute of Microelectronics and Optoelectronics, Warsaw, Poland
[2] Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw, Poland
[3] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: One of the technological challenges in fabrication of GaN-based TrenchMOSFETs is achieving a high-quality trench with nondamaged sidewalls which will work as transistor channel. Key technological goal include creating a trench with an appropriate depth (usually at least 1 μm), rounded edges at the bottom of the channel to reduce the electric field crowding effect, and smooth sidewalls. These factors contribute to lowering the on-state resistance ($R_{S(ON)}$) and improve breakdown capability of transistors.Additionally, minimizing defects caused by plasma etching is crucial for better quality of gate interface and then the proper functioning and long-term reliability of the device.

A two-step trench processing method has been used as an effective solution. First, plasma etching is performed to achieve the desired depth, followed by wet etching. The wet etching step smooths the channel walls and eliminates damage introduced during plasma etching. Proper selection of etching parameters is crucial for achieving a high-quality channel on trench wall in the transistors, which directly improves the performance and reliability of GaN-based TrenchMOSFET transistors.

In this study, we present a detailed comparison of two Cl_2-based plasma etching methods with BCl_3 or $SiCl_4$ addition. Both reagents are widely used in GaN processing technologies, but they differ in etching efficiency and their impact on channel surface quality. One of the key aspects analyzed in this study is the effect of reactive ion etching (RIE) power. Reducing RIE power decreases the energy of ions bombarding the surface, thereby limiting the number of defects and structural damage while also affecting the etching rate. Optimizing plasma etching parameters - such as RIE power, gas flow ratio, and chamber pressure - enhances the selectivity of GaN etching relative to the silicon dioxide mask.

The increase in RF power causes the phenomenon of microtrenching at the bottom of the etched structure. In the case of chlorine plasma with the addition of $SiCl_4$ this phenomenon is only visible when the table RF power increases over 70W.

This work was supported by The National Centre for Research and Development under Agreement nr TECHMATSTRATEG-III/0003/2019 for project "Complete vertically integrated technological chain for vertical GaN-on-GaN power electronics: from GaN substrate to Intelligent Energy Bank.

ED-Mon-P55 - Vertically Integrated Two-Memristors-One-Cell Nonvolatile Resistive Random-Access Memory through Nitrogen Vacancy Engineering

4. Electronic devices
Haijiao Ma[1]
Xianqin Liu[1], Yue Hao[1], Jincheng Zhang[1]
[1] Xidian University

Abstract text: Aluminum nitride based memristors have shown ultrafast switching at or even below nanoseconds. However, the on/off ratio, lifespan and endurance of nitride memristors are limited. Here we realized high performance AlN memristive through nitrogen vacancy engineering. The on/off ratio of the AlN memristors could be as high as a few hundreds to thousands and can be improved to 10^6 using one device cell consisting of two memristors connected in parallel with common bottom electrode (Two-Memristors-One-Cell, 2M1C). We further designed and fabricated vertically integrated 2M1C device as a nonvolatile ReRAM on 2-inch sapphire and silicon wafers. These integrated 2M1C devices possess high performance with an endurance of 10^4 and a retention up to 10^5 s indicating a promising nonvolatile memory.

ED-Mon-P56 - Achieving Low Ohmic Contacts on n-type AlN with Contact Resistivity at 10-4 Ω·cm2 Level

4. Electronic devices

Haicheng Cao[1]
Mingtao Nong[1], Xiao Tang[1], Biplab Sarkar[2], Ying Wu[1], Xiaohang Li[1]
[1] Computer, Electrical and Mathematical Science and Engineering (CEMSE) Division, King Abdullah University of Science and Technology, Jeddah, Saudi Arabia
[2] Department of Electronics and Communication Engineering, Indian Institute of Technology, Roorkee, Uttarakhand, India

Abstract text: Aluminum nitride (AlN) is ideal for high-power electronic devices due to its ultrawide bandgap, high breakdown strength, superior thermal conductivity, and exceptional stability. MOCVD remains the dominant method for commercial AlN growth, yet the high dopant ionization energy restricts n-type AlN's carrier concentration, leading to high ohmic contact barriers. The leading strategy involves n-type graded AlGaN layers on n-type AlN films, though this requires precise MOCVD parameter control and additional growth and etching steps. Alternatively, optimizing the metallization process—such as incorporating vanadium or thin silicon nitride as contact layers and inducing nitrogen vacancies through rapid thermal annealing (RTP)—provides a more direct solution. This study presents optimized metallization strategies achieving a record-low contact resistivity of 10^{-4} Ω·cm² on n-type AlN, eliminating the need for AlGaN gradient layers and demonstrating the potential for high-performance AlN-based power electronics.

AlN layers were grown on AlN/sapphire substrates via MOCVD, incorporating a 250 nm Si-doped AlN layer (Si: 6.4×10^{18} cm^{-3}). Two contact metal stacks, TiAlTiAu and TiAlTi, were sputtered and subjected to RTP in N_2 at temperatures between 800°C and 950°C for 30 to 120 seconds. Post-annealing, contact characteristics were assessed using CTLM, while cross-sectional TEM analysis provided structural and compositional insights into the metal/semiconductor interface. Surface morphology analysis revealed a rougher surface for TiAlTiAu due to Au interdiffusion. Electrical characterization showed that the TiAlTi stack exhibited more linear I-V characteristics and significantly lower knee voltage, reducing the on-resistance of AlN SBDs by a factor of 10. TEM analysis indicated that TiAlTi formed a thinner Al-Ti-N interlayer (1–6 nm), whereas TiAlTiAu produced a thicker Al-N interlayer (25–35 nm). The thinner interlayer in TiAlTi improved carrier tunneling, reducing resistivity. Within the TiAlTi stack, increased annealing temperature and duration further lowered specific contact resistivities, reaching a minimum of 5.82×10^{-4} Ω·cm² at 950°C for 90 seconds, with a contact resistance Rc of 82.7 Ω·mm. These findings emphasize the potential of optimized metallization in achieving low-resistivity contacts on n-AlN, advancing AlN-based power electronics.

ED-Mon-P57* - Atomic Layer Etching Enables Near-Ideal Schottky Contacts on Si-Doped AlN on sapphire

4. Electronic devices

Haicheng Cao[1]
Zixian Jiang[1], Mingtao Nong[1], Tingang Liu[1], Zhiyuan Liu[1], Saravanan Yuvaraja[1], Xiao Tang[1], Biplab Sarkar[2], Ying Wu[1], Xiaohang Li[1]
[1] Computer, Electrical and Mathematical Science and Engineering Division, King Abdullah University of Science and Technology, Jeddah, Saudi Arabia
[2] Department of Electronics and Communication Engineering, Indian Institute of Technology, Roorkee, Uttarakhand, India

Abstract text: Schottky contacts is crucial for the SBDs and MESFETs' performance, affecting key parameters such as ideality factor (n), rectification ratio, switching speed, and breakdown voltage. As a prime ultrawide bandgap semiconductor, AlN is promising for power devices requiring ultra-high voltage control. However, achieving near-ideal Schottky contacts on AlN is challenging due to its high oxygen sensitivity. To address this, various pretreatment methods have been used, mainly classified into wet-etching (e.g., BOE, HCl) and low-power RIE. These methods aim to remove the surface oxide layer and minimize surface damage. However, air exposure during fabrication inevitably leads to oxidation or/and contamination, making near-unity Schottky contacts difficult to achieve.

This study employed Atomic Layer Etching (ALE), a low-power, slow-etching technique that effectively removes the oxide layer and prevents further oxidation, enabling near-unity Schottky contacts. The epitaxial layer comprised a 1.7 μm u-AlN and a 1 μm Si-doped AlN with a Si concentration of 4.6×10^{18} cm^{-3}. Two SBD devices were fabricated, both using Ti/Al/Ti as the ohmic metal stack and Ni/Au as the Schottky metal. Before Schottky contact formation, both samples underwent a 30 min BOE cleaning to remove the native oxide layer. One sample then received an additional 100-cycle ALE pretreatment. AFM results showed a 6 nm etch depth and reduced RMS roughness, indicating a smoother surface post-treatment. The ideality factor of the treated devices decreased from 1.76 to 1.39, and the barrier height increased from 1.2 eV to 1.43 eV. At 300°C, n approached near unity at 1.09. This improvement is attributed to oxide layer removal and the formation of a uniform, smoother interface.

XPS analysis showed the disappearance of C and O satellite peaks after treatment, indicating reduced surface contamination. This conclusion was further evidenced by a decrease in donor-like interface traps (Dit) and a two-order-of-magnitude reduction in leakage current (Ion/Ioff ratio exceeding 2×10^{7} at ±10V). Additionally, enriched VAl inhibit new oxide layer formation, making the AlN surface less oxygen-sensitive and eliminating Al-O bonds in XPS spectra. These findings underscore ALE's potential in achieving high-performance AlN Schottky contacts, advancing AlN-based power electronics.

Poster Session 2

2025-07-08
17:00 - 19:00
Poster Session 2

GR-Tue-P2* - Interfacial Structure and Stability of ScAlMgO4-GaN Interfaces: Implications for Mg and Sc Diffusion and Doping Behavior

1. Growth

Weifang Lu[1]
Yueping Hu[1], Yang Sun[1], Xu Yang[2], Jinchai Li[2], Kai Huang[2], Zhaoxia Bi[3], Cheng Li[1], Junyong Kang[1], Songyan Chen[1], Rong Zhang[2]
[1] Xiamen University
[2] Xiamen University; Future Display Institute of Xiamen
[3] Future Display Institute of Xiamen

Abstract text: Heterogeneous growth on small mismatch substrates, like $ScAlMgO_4$ (SCAM), has been proposed to improve the quality of InGaN/GaN quantum wells. Despite successful growth methods such as MOVPE and MBE, the introduction of Mg atoms into GaN from SCAM remains unclear, with potential effects on device performance. In this work, the structures and stability of SAM-GaN interfaces were systematically investigated through first-principles calculations to understand the diffusion mechanisms of Mg and Sc atoms from the SAM substrate into GaN under different structural configurations. Energy calculations identify the Sc–O-terminated surface as the most stable configuration for SAM, with a secondary stable configuration consisting of one Mg(Al)–O layer above the Sc–O layer. Interfacial energy calculations reveal distinct preferences for GaN growth polarity, with the Sc–O surface favoring bonding with Ga atoms and promoting N-polar GaN growth, while the Mg–O surface preferentially bonds with N atoms, leading to Ga-polar growth. Defect formation energy analysis shows that Mg and Sc atoms do not easily diffuse individually from SAM into GaN. In the Sc–O-terminated structure, excess Mg can occupy six-coordinated interstitial sites within GaN. However, direct diffusion of Sc atoms into GaN through the interface is unlikely in this structure. On the other hand, in the Mg–O-terminated structure, dissociated Sc atoms in the interfacial region can bind to interstitial sites within GaN, a phenomenon not observed in the Sc–O terminated configuration. These findings underscore the critical role of the interfacial structure in controlling Mg and Sc doping behavior, which is essential for the growth of lattice-matched GaN on SAM substrates.

GR-Tue-P3* - Boron for Strain-Compensation in BInGaN: Effects on Luminescence Properties

1. Growth
Olivia Shortall[1]
Vitaly Z. Zubialevich[2], Peter J. Parbrook[1]
[1] Tyndall National Institute, University College Cork, Lee Maltings, Dyke Parade, Cork, Ireland; Department of Electrical and Electronic Engineering, University College Cork, Cork, Ireland
[2] Tyndall National Institute, University College Cork, Lee Maltings, Dyke Parade, Cork, Ireland

Abstract text: Efficient III-nitride-based red LEDs are crucial for integration into RGB microLED displays. While blue and green InGaN LEDs have achieved high wall plug efficiencies (WPEs) (80% and 50% respectively), their red counterpart suffers from efficiency loss due to the compressive strain and plastic relaxation, with a maximum reported WPE in the single digits. Due to its small lattice parameter, boron nitride can compensate for this strain when alloyed with InGaN. Initial estimates of the bowing parameter suggest that the incorporation of small amounts of B will not significantly increase the bandgap. Here, we investigate the impact of B on InGaN emission in the blue/green, with a view to ultimately moving to longer wavelengths.

Four (B)InGaN/GaN three quantum well (QW) structures were grown by MOCVD in a showerhead-type reactor. A quasi-2*T* approach was implemented, where temperature (*T*) was kept at 690°C for the QW and the first ~1 nm of the quantum barrier (QB). The temperature was then ramped to higher values for the rest of the QB (810°C, 860°C, 910°C and 960°C). For each T_{QB}, two samples were grown with B/III ratios of 0% (reference) and 1%. Also, we studied the effect of replacing the low *T* (LT) QW GaN cap with AlN in both cases.

Samples were characterised by *T*-resolved photoluminescence (PL) and LT PL excitation (PLE). PL results showed a blueshift of near-bandedge emission with B, with reduced intensity and apparent IQE. All samples deviated from Varshni behaviour, as expected. AlN caps caused a redshift in the NBE peak for both reference and B-containing samples compared to GaN, but did not alter the effects observed by adding B to the QW.

For GaN-capped samples, PLE results allowed clear identification of the (B)InGaN edge and results were consistent with expected trends. For the AlN-capped reference samples, PLE indicated a change in carrier transport from the QBs to the QWs. In both cases, the B-containing samples demonstrated weaker intensity and blue shifted, making PLE analysis more challenging.

These findings indicate that under the studied growth conditions, boron dramatically alters the PL properties. In particular, the blueshift is indicative of either In content suppression or that B is acting non-radiatively in high In content regions. Further work with modified growth conditions is planned to both understand and improve performance.

GR-Tue-P4 - Evaluation of growth temperature dependency in BGaN growth using AlGaN template on QST substrate

1. Growth

Atsuhiro Hayashi[1]
Shun Nishikawa[1], Eito Kokubo[2], Genichiro Wakabayashi[3], Yoshio Honda[2], Hiroshi Amano[2], Kota Matsumoto[4], Norikazu Ito[4], Taketoshi Tanaka[4], Ken Nakahara[4], Yoku Inoue[1], Toru Aoki[1], Takayuki Nakano[1]
[1] Shizuoka University, Hamamatsu 432-8561 Japan
[2] Nagoya Universty, Nagoya 464-8601 Japan
[3] Kindai University, Higashiosaka 577-8502 Japan
[4] ROHM Co., LTD., Kyoto 615-8585 Japan

Abstract text: BGaN containing B atoms with a large neutron captured cross section is expected to be a novel neutron detecter. In previous studies, BGaN has been grown on the GaN buffer layers on various substrates such as Al_2O_3 and Si. However, it has been difficult to fabricate the high B composition and high-quality BGaN growth, because the tensile strain and crack generation were caused by the lattice constant of BGaN on the GaN buffer layer. Recently, QST (Qromis Substrate Technology) substrates have been expected as a new GaN-based semiconductor substrate because they have the same coefficient of thermal expansion as GaN. Furthermore, an AlGaN buffer layer on the QST substrate allows BGaN growth with reduced tensile strain. Therefore, in this study, the lattice constant of the buffer layer was controlled by changing the Al composition, and BGaN growth with different strains was evaluated. In BGaN growth by AlGaN/QST template with compressive strain, BGaN films which were affected by changing growth temperature was also evaluated. BGaN films were fabricated by metal organic vapor phase epitaxy (MOVPE). The templates were used GaN templates with GaN buffer layers on Si and QST substrate, and $Al_xGa_{1-x}N$ templates with $Al_xGa_{1-x}N$ buffer layers. BGaN layers were grown on each template for structural characterization. Furthermore, BGaN layers were grown at 900～1000 ℃ for growth temperature dependency characterization. The strain in the BGaN layer were evaluated by X-ray reciprocal space mapping measurement. From the results, BGaN layer was exposed to compressive strain in all buffer layer. Although the BGaN layer would be exposed to tensile strain due to the GaN layer, the X-ray RSM measurement result indicates that the BGaN layer may be growing under compressive strain due to the influence of the underlying AlGaN layer of the GaN template. Next, impact of growth temperature in BGaN layer on $Al_{0.53}Ga_{0.47}N$ template with Si and QST substrates was evaluated by X-ray RSM measurement. The displacement of the BGaN peak position of the QST substrate was smaller than that of the Si. This difference may be due to the thermal expansion coefficient of the substrate. These results indicate that the possibility of high-quality BGaN films on QST substrate by strain-controlled using AlGaN buffer layer. Moreover, BGaN diode was fabricated, and neutron detection characteristic was evaluated.

GR-Tue-P5 - Evaluation of radiation tolerance on BGaN detectors at KUR

1. Growth

Ryohei Kudo[1]
Tatsuhiro Sakurai[1], Eito Kokubo[2], Tetsuichi Kishishita[3], Yoshinori Sakurai[4], Hiroshi Yashima[4], Takahiro Makino[5], Takeshi Ohshima[5], Yoshio Honda[2], Hiroshi Amano[2], Yoku Inoue[1], Toru Aoki[1], Takayuki Nakano[1]
[1] Shizuoka University, Hamamatsu 432-8561, Japan
[2] Nagoya University, Nagoya 464-8601, Japan
[3] High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
[4] KURNS. Kyoto University, Sennan 590-0494, Japan
[5] National Institutes for Quantum and Science and Technology (QST), Takasaki 370-1292, Japan

Abstract text: Nuclear instrumentation system is an important technology for the safe operation of nuclear reactors. In the system, the operation for neutron detection in harsh environments, such as high-temperature and high-radiation atmospheres, is necessary. In the High Temperature Gas-cooled Reactor (HTGR) as the new type of nuclear reactor, internal reactor temperature becomes over 600 °C and neutron flux becomes over 10^{13} $n \cdot cm^{-2} \cdot s^{-1}$. Then, the development of new nuclear instrumentation technology with harsh environments tolerance is expected. A BGaN, which is a wide-bandgap semiconductor, contains B atoms with a large neutron capture cross-section area. Such BGaN devices are being developed as a new neutron detection semiconductor material. In the previous study, alpha-particle detection using a BGaN diode was observed at 300 ºC. On the other hand, the radiation tolerance for BGaN diodes has not yet been evaluated. Therefore, in this study, the radiation tolerance of BGaN diodes was evaluated at the Kyoto University Research reactor (KUR).
BGaN films were grown by metal organic vapor phase epitaxy (MOVPE), and BGaN diodes were fabricated using grown BGaN films. The BGaN layer thickness was about 1 μm. Alpha-particles irradiation was used ^{241}Am (5.41 MeV, 3.94 MBq). Neutron irradiation measurement was carried out at KUR.
In the result of 2.3-MeV-alpha-particles irradiation measurement, the peak position and FWHM value of energy spectrum were constant in all 48 hours of irradiation time. This result means that the alpha-particles irradiation was not affected to device properties. In the neutron irradiation measurement, two energy peaks originating from neutron detection were confirmed. The phenomenon indicates that some of the charged particles generated by the neutron capture reaction escaped outside the sensitive layer because of the 1-μm-BGaN layer. The peak position and FWHM value of the high-energy neutron detection peak are similar to those of the alpha-particles energy spectrum. This result suggests that the energy of 2.3 MeV was detected in neutron irradiation. The peak position and FWHM value were stable during 24 hours of neutron irradiation, and there was no effect of neutron irradiation to device properties. These results indicate that the BGaN diodes have the potential for use as novel nuclear instrumentation devices.

GR-Tue-P6 - Feasibility of molecular beam epitaxy of boron-nitride-arsenide highly mismatched alloys.

1. Growth

Tin S. Cheng[1]
Jonathan Bradford[1], Leo Norman[2], Xiaoyang Ji[2], Arpit Nandi[2], Gerardo M. Alanis[3], Stuart Robertson[4], Paul R. Edwards[5], James W. Pomeroy[2], David Cherns[2], Christopher J. Mellor[1], Robert W. Martin[5], Peter H. Beton[1], Martin Kuball[2], **Sergei V. Novikov**[1]
[1] School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK
[2] Center for Device Thermography and Reliability, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, UK
[3] Department of Materials, University of Oxford, Oxford, OX1 2JD, UK
[4] Loughborough Materials Characterisation Centre, Loughborough University, LE11 3TU, UK
[5] Department of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, UK

Abstract text: The last decades have seen very rapid theoretical and experimental progress in studies of group III-N-V highly mismatched alloys (HMAs). HMAs are a class of semiconductor alloys whose constituents are distinctly different in terms of size, ionicity and/or electronegativity. We have successfully grown GaN-based layers alloyed with GaAs, GaSb and GaBi compounds using plasma-assisted molecular beam epitaxy (PA-MBE). We have achieved an enhanced incorporation of As, Sb and Bi by growing the layers at extremely low temperatures (down to about 100ºC). Although the layers become amorphous for high As, Sb and Bi content, the measured composition dependence of the optical absorption edges indicates that the amorphous HMAs samples have a short-range order, resembling random crystalline alloys.

Due to a wide range of the optical properties, the B-N-As HMAs can potentially provide the fundamental basis for boron-based photonics and electronics. There is a large mismatch of the lattice parameter and bulk modulus of BN and BAs binary semiconductors. The energy bandgap bowing was theoretically predicted to be very strong for BNAs alloys with intermediate compositions predicted to become semimetals. Binary BN and BAs are indirect band gap semiconductors with a crossover predicted to direct band gap for intermediate BNAs compositions. However, to the best of our knowledge, incorporation of arsenic to boron-nitride or nitrogen to boron-arsenide have never been experimentally explored, and BNAs semiconductor alloys have never been demonstrated.

BNAs layers were grown by PA-MBE on diamond, 3C-SiC/Si and sapphire substrates over a wide temperature range from 150ºC to 820ºC. We have explored the epitaxy of BNAs alloys from binary BN to binary BAs. The incorporation of boron, arsenic and nitrogen and properties of the layers have been studied by a wide range of characterisation techniques. We do not observe formation of BNAs alloys at low epitaxial temperatures. However, we have confirmed incorporation of arsenic into boron nitride layers grown at the temperatures up to 760ºC. Arsenic-doped BN layers grown at high temperatures demonstrate a strong change in their optical properties. We will present results on the thermal conductivity of the BNAs layers, grown under different MBE conditions. Feasibility of PA-MBE of BNAs highly mismatched alloys will be discussed.

GR-Tue-P7 - Layered Boron Nitride - Heterointegration and applications

1. Growth

Suresh Sundaram[1]
Phuong Vuong[1], Vishnu Ottapilakkal[2], Thi May Tran[2], Tarik Moudakir[3], Simon Gautier[3], Jean Paul Salvestrini[1], Paul L. Voss[4], Abdallah Ougazzaden[4]
[1] Georgia Tech-Europe, 2 rue Marconi, 57070 Metz, France
[2] CNRS, IRL 2958 Georgia Tech - CNRS, 2 rue Marconi, 57070 Metz, France
[3] Institut Lafayette, 2 rue Marconi, 57070 Metz, France.
[4] Georgia Institute of Technology, School of Electrical and Computer Eng., Atlanta, GA 30332, USA

Abstract text: Layered boron nitride (h-BN) integration with existing conventional device structures have recently attracted lots of interest as it offers exotic functionalities and dramatic performances [1, 2, 3]. Especially, h-BN serves as an active dielectric in novel devices, buffer for III-nitrides growth and enables elegant liftoff of III-nitride device structures from host substrates.

In the present investigation, exploration of MOVPE van der Waals epitaxial growth of h-BN and successful demonstration of its integration with conventional III-nitride and other devices is reported. III-nitride material based light emitting diode (LEDs) stack growth on BN by MOVPE has been successfully scaled up to 6" diameter [4]. In addition, Vertical integration of these LED structures on BN grown by van der Waals epitaxy with red color LEDs grown on graphene by remote epitaxy for realization of full color micro-LEDs display will be discussed [1]. Controllable growth of this 2D materials on patterned templates leads to high quality BN growth on specific/defined crystalline areas. Subsequently, using these BN on patterned templates, III-nitride based device arrays were realized which is transferrable and individually addressable [5, 6]. These growth experiments on scaling up and heterointegration gives a very important insight on the potential commercialization path on the use of 2D materials in novel device structures.

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GR-Tue-P8* - Sputtered wurtzite-type (Al,Hf)N thin films: Synthesis, crystallographic texture, and surface-acoustic-wave generation

1. Growth

Laura I. Wagner[1]
Verena Streibel[1], Mingyun Yuan[2], Ian D. Sharp[1]
[1] Walter Schottky Institute and Physics Department, TUM School of Natural Sciences, Technical University of Munich, 85748 Garching, Germany
[2] Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., 10117 Berlin, Germany

Abstract text: The development of ternary nitrides offers enormous potential for a broad range of future technologies. In terms of wide bandgap ternary nitrides, aluminum transition metal nitride [(Al,TM)N] compounds are especially promising, as exemplified by the emergence of (Al,Sc)N. However, alternative TM elements within the (Al,TM)N space remain largely unexplored, despite these compounds offering potential advantages, such as increased piezoelectric coefficients and reduced reliance on rare earth elements. For example, TMs such as Hf, Zr, and Ti have recently been predicted to offer similar piezoelectric enhancements as Sc when incorporated into AlN. [1] In this work, we explore the deposition of wurtzite-type aluminum hafnium nitride ($Al_xHf_{1-x}N$) thin films by reactive co-sputtering on different substrates, emphasizing the optimization of synthesis parameters to tailor crystallographic texture and piezoelectric properties for surface-acoustic-wave (SAW) device applications. For investigation of the $Al_xHf_{1-x}N$ composition space, the Hf content is tuned by scaling the power applied to the metallic Hf and Al targets and using Ar/N_2 sputtering atmospheres. Post-deposition annealing in ammonia is used to further tune the structural quality, as well as residual oxygen impurity concentrations. Detailed structural analyses of the polycrystalline thin films using X-ray diffraction reveal wurtzite phase material with a preferred c-axis orientation and increasing lattice parameters with Hf concentrations up to 10 at.%. Complementary piezoresponse measurements establish a correlation between film composition and piezoelectric coefficient d_{33}. Furthermore, we demonstrate the efficient generation of GHz SAWs with minimal propagation loss in $Al_xHf_{1-x}N$ thin films sputtered on sapphire. The inclusion of Hf compensates for the lower structural quality typically observed in sputtered films compared to those produced by epitaxial growth methods such as molecular beam epitaxy (MBE). This study demonstrates the possibility of synthesizing wurtzite $Al_xHf_{1-x}N$ using the highly versatile and inexpensive sputtering method. These $Al_xHf_{1-x}N$ films can potentially become a key material platform for high-frequency SAW applications, spanning from sensing to telecommunication.

[1] Adv. Electron. Mater. 2023, 9, 2201187

GR-Tue-P9 - Structural and optical properties of ultrathin B and BN layers grown on sapphire by molecular beam epitaxy

1. Growth

Emil Mihai Pavelescu[1]
Cosmin Romanitan[1], Iuliana Mihalache[1], Raluca Gavrila[1], Marius Stoian[1], Gabriel Craciun[1], Silviu Vulpe[1], Cosmin Obreja[1], Valentin Feies[2], Andrei Dragulinescu[2], Marian Vladescu[2], A.C. Iancu[3], Cristian Mihail Teodorescu[3], Maria de la Mata[4], M. Herrera[4], H. Tornatzky[5], S.I. Molina[4], Esperanza Luna[5]
[1] National Institute for Research and Development in Microtechnologies, Erou Iancu Nicolae 126A, 077190 Voluntari, Romania
[2] National University of Science and Technology POLITEHNICA Bucharest, Iuliu Maniu Avenue 1-3, 061071, Bucharest, Romania
[3] National Institute of Materials Physics, Atomiştilor 405A, 077125 Măgurele, Romania
[4] Departamento de Ciencia de los Materiales, I. M. y Q. I., IMEYMAT, Universidad de Cadiz, Puerto Real, 11510, Spain
[5] Paul-Drude-Institut für Festkörperelektronik, Leibniz-InstitutimForschungsverbundBerline.V.,Hausvogteiplatz,10117Berlin,Germany

Abstract text: The growth of wafer-scale high-quality sp2-hybridized B (borophene) and boron nitride (BN) materials, especially hexagonal BN (h-BN), on appropriate substrates is the prerequisite for their various potential applications. Recently, the scalable growth of mono and few-layer h-BN has been achieved on catalyzing metal substrates [1] whereas borophene has been synthesized only on metallic surfaces [2]. However, the use of metal substrates usually needs a complicated, contamination-prone and cost-intensive additional transfer process from metal substrates to semiconducting or insulating substrates for most device applications. Therefore, the direct growth of few-layer h-BN and B with device quality on microelectronic compatible dielectric substrates is highly desirable.
In this work, thin B and BN layers have been grown by nitrogen plasma-assisted molecular beam epitaxy on c-plane sapphire substrate at two extreme temperatures, 50 and 1000 ^{o}C. A sp^2-hybridized BN material has been formed at both temperatures however with different polytypes, the h-BN and the less ordered turbostratic BN (t-BN) at the high and low temperature, respectively. Besides the B_3O_2 and B suboxides, the crystalline boron, likely of rhombohedral symmetry, has also been observed on the surface of sapphire, especially at the higher growth temperature. The thickness of the deposited material has been seen to noticeably decrease with the increase in the temperature of growth, suggesting an important temperature-dependent sticking coefficient for B. An enhancement in elastic modulus and hardness of the B(N) layers has also been noticed with the decrease in deposition temperature towards near room temperature.
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GR-Tue-P10 - The lift-off technology of GaN-based electronic and optoelectronic devices using Hexagonal BN-assisted van der Waals Epitaxy

1. Growth

Renfeng Chen[1]
Junxi Wang[1], Jinmin Li[1], **Tongbo Wei**[1]
[1] Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

Abstract text: The introduction of h-BN in GaN epitaxy provides much novel interface configuration strategy of heteroepitaxy, profoundly influencing the development direction of growth and transfer of single crystal thin film. In this work, we demonstrate the positive role of the exfoliation of GaN-based devices using van der Waals epitaxy by h-BN. Based on the low-temperature GaN nucleation layer, the h-BN-assisted laser lift of technology has been discussed, effectively reducing the laser threshold power from 0.43W to 0.15W. We found that the insertion of thin h-BN slightly affects the material quality of GaN. Under the condition of thickness less than 1.2nm, the multiple quantum wells grown in GaN/h-BN/Sapphire template has not observed with obvious attenuation of quality. The roughness of the exfoliation surface with 0.6nm h-BN obtain about 38% reduction, and the fabricated vertical LED exhibits reduced electric leakage phenomenon. By contrasting the Raman results of different thickness of h-BN, we proposed the insertion of thin h-BN induce in-plane compressive stress in the condition of GaN nucleation layer, Which accumulates deformation potential energy in the GaN-based thin-film devices. Meanwhile, the TEM results show there might be the phenomenon of the diffusion of O from the substrate, forming a thick mixing layer around the interface of epilayer and substrate. These combined effects finally lead to the reduction of laser threshold power during laser lift-off process with the assist of h-BN. This work provides a technical guidance for combining the h-BN-assisted van der Waals epitaxy with industry.

GR-Tue-P11* - Van der Waals epitaxy h-BN/AlN back barrier with controllable boron-diffusion for high-performance AlGaN/GaN HEMTs

1. Growth

Haidi Wu[1]
Jing Ning[1], Yue Hao[1], Jincheng Zhang[1]
[1] State Key Laboratory of Wide-Bandgap Semiconductor Devices and Integrated Technology, Faculty of Integrated Circuit, Xidian University, Xi'an 710071, China

Abstract text: Abstract

The growth of single-crystal III-nitride films with a low stress and dislocation density is crucial for the semiconductor industry. Van der Waals Epitaxy (vdWE) is a highly desirable method owing to the recent application of high-performance High Electron Mobility Transistors (HMETs). However, inhibiting crystal merging due to the lack of nucleation sites has been a challenge in crystallization; two-dimensional material interface unable to effectively participate in carrier transport, often leading to a poor device performance. Here， we report a innovative growth of nitride heterostructures directly on h-BN by MOCVD, achieving high-quality III-nitride epitaxy and high-performance AlGaN/GaN HEMTs.

By using aluminum ion implantation to pretreat the h-BN intermediate layer, creating a surface rich in unsaturated bonds as nucleation sites for highly oriented nitride growth. The h-BN layer effectively released biaxial stress (0.138GPa) and reduced the dislocation density in the epitaxial layer by an order of magnitude. In addition, the 2DEG concentration of h-BN/AlN back barrier AlGaN/GaN HEMT by van der Waals epitaxy reached 8.80×10^{12} cm^{-2} and the electron mobility was 2091.3 $cm^2/V \cdot s$, with a high On/Off ratio of 10^{10}. This study is expected to provide a revolutionary technology for the epitaxial growth of high-quality nitride thin films and provide opportunities for the scalable application of h-BN thin films in HEMTs.

Keywords: III-Nitride epitaxy, Van der Waals epitaxy, AlGaN/GaN HEMT, h-BN

GR-Tue-P12 - Van der Waals β-Ga_2O_3 Thin Films on High-Thermal-Conductivity Polycrystalline Diamond/h-BN Related Two-Dimensional Materials

1. Growth

Zhichun Yang[1]
Jing Ning*[1], jincheng zhang*[1], yue hao[1]
[1] Xidian University, Xi'an 710071, China

Abstract text: The self-heating effect in wide bandgap semiconductor devices highlights the importance of using epitaxial Ga_2O_3 on diamond substrates for efficient thermal management. However, the industrial use of this combination is hindered by the unavailability of large-scale single-crystal diamond wafers and the significant lattice mismatch. This study introduces a novel approach by growing van der Waals β-Ga_2O_3 (VdW-β-Ga_2O_3) on high-thermal-conductivity polycrystalline diamond. The interaction between the single-crystal thin film and the polycrystalline substrate is modified by van der Waals forces. Tunable growth of the (-201) VdW-β-Ga_2O_3 was achieved by exploiting the mismatch between graphene and the varying oxygen surface densities of different crystal orientations, as well as their dependence on oxygen partial pressure. The films exhibited high crystallinity, with a full width at half maximum of 0.21° and a root mean square roughness of 9.79 nm. Graphene helped mitigate interfacial thermal expansion stress, resulting in an external equivalent thermal conductivity more than three times that of Ga_2O_3 material. Photodetectors made from these films showed a photo-to-dark current ratio of 10^5 and a responsivity of 210 A/W, demonstrating the practicality and significance of this approach.

GR-Tue-P13 - Amorphous Carbon Films used for Remote Epitaxy of cubic Gallium Nitride on 3C SiC (001) Substrates

1. Growth

Donat Josef As[1]
Pascal Mahler[1], Mario Littmann[1], Tobias Henksmeier[1], Dirk Reuter[1]
[1] Paderborn University, Department of Physics, Warburger Str. 100, 33089 Paderborn, Germany

Abstract text: Remote epitaxy (RE) of GaN is a promising technology that can overcome the limitation of conventional epitaxy [1]. One advantage of this method is that the influence of the lattice mismatch and differences in thermal expansion coefficients are mitigated and enables hetero-epitaxy with reduced strain and dislocations. For the metastable cubic GaN no natural GaN substrates exist. Up to now the substrate of choice for hetero-epitaxy is 3C-SiC (001) with a lattice mismatch of about 3.2%, still resulting in a dislocation density of about $10^9 cm^{-2}$ in cubic GaN epilayers [2]. First experiments on RE growth of cubic GaN on 3C-SiC covered by one monolayer thick Graphene - created by a CVD process on copper foils and transferred to the 3C-SiC substrate - showed that the success of RE strongly depends on quality of Graphene [3]. In CVD-Graphene a lot of grain boundaries and wrinkles exist, where the electrostatic potential from the substrate is disturbed and no longer acts as a seed material for the cubic phase of GaN, but the GaN grows in its natural hexagonal phase. Therefore, to reduce the hexagonal inclusions a smooth sp^2-hybridized 2D-interlayer has to be used. Recently, a low temperature fabrication of amorphous carbon films as a universal template for RE was developed by us, which may be useful to avoid these grain boundary effects [4].

In this work we investigate the use of thin **amorphous carbon films** for RE of cubic GaN on 3C-SiC substrates and compare it with cubic GaN grown on a monolayer CVD - Graphene covered substrates. A monolayer-like thick amorphous carbon or graphene monolayer is introduced between the substrate and the epilayer. On top of the interlayer the cubic GaN is grown by plasma-assisted molecular beam epitaxy. Scanning electron microscopy, atomic force microscopy, high resolution X-ray diffraction and low-temperature photoluminescence measurements are used to characterize the samples. All characterization methods demonstrate that carefully prepared amorphous carbon films are well suited for RE and that hexagonal inclusions are reduced by at least one order of magnitude.

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GR-Tue-P14* - Atomic energy modulated epitaxy of N-polar AlN and GaN

1. Growth

Ran Feng[1]
Ping Wang[1], Tao Wang[1], Haotian Ye[1], Rui Wang[1], Bo Shen[1], Xinqiang Wang[1]
[1] State Key Laboratory for Mesoscopic Physics and Frontiers Science Center for Nano-optoelectronics, School of Physics, Peking University, Beijing 100871, China

Abstract text: Nitrogen-polar (N-polar) III-nitride semiconductors are promising for applications in deep ultraviolet optoelectronic devices and high-frequency, high-power electronic devices. However, their heteroepitaxy presents significant challenges compared to metal-polar counterparts. The strong atomic bonding of N-polar surface restricts nitrogen adatoms diffusion, while the Ehrlich–Schwoebel barrier (ESB) at the step edges further inhibits adatoms migration towards adjacent terrace, limiting step expansion and coalescence[1,2]. These effects degrade surface morphology, interface quality, and overall crystal integrity.

In this work, we developed an atomic energy modulated epitaxy approach, enabling precise control over the energy (or temperature) of nitrogen atoms. Employing this method, we achieved high-quality heteroepitaxy of N-polar AlN and GaN on SiC substrates utilizing a plasma-assisted molecular beam epitaxy (MBE) system. The resulting films exhibit highly ordered N-polar atomic stacking, atomically smooth surfaces and interfaces, and high crystal quality. Theoretical analyses reveal that the energy of nitrogen atoms critically influences the diffusion barrier and lifetime of adatoms, higher energies promote defect formation and mound-shaped surface. Using this technique, we have grown N-polar GaN-based high electron mobility transistor (HEMT) structures on SiC substrates, achieving enhanced mobility and high carrier concentrations. This work provides insights into N-polar III-nitrides epitaxy dynamics, offering a pathway toward next-generation high-frequency and high-power electronic devices.

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GR-Tue-P15* - Crack-Free Growth of Thick Gallium Nitride on Sapphire for High-Voltage Applications

1. Growth

M Nazri Kasuan[1]
Ahmad Shuhaimi Abu Bakar[1], Rizuan Norhaniza[1], Nor Hapishah Abdullah[1], Muhammad Iznul Hisyam[1], Nur Azeni Mohamad Rusop[1], Muhammad I M Abdul Khudus[1]
[1] LDMRC, Universiti Malaya, Kuala Lumpur, Malaysia

Abstract text: We report the successful growth of a ~10 µm crack-free gallium nitride (GaN) epitaxial structure on sapphire using a Taiyo Nippon Sanso SR-2000 metal-organic chemical vapor deposition (MOCVD) system. The structure comprises a 3 µm unintentionally doped GaN base layer on a low-temperature base layer, followed by a 2 µm n-doped GaN drain contact layer, a 5 µm thick drift layer, a 700 nm Mg-doped GaN (p-GaN) layer, and a 200 nm n-GaN source contact layer. The Mg-GaN was grown at 950°C to enhance Mg incorporation, while the other main epitaxial layers were deposited at 1150°C. X-ray diffraction (XRD) analysis confirmed high crystalline quality, with full width at half maximum (FWHM) values of 213 arcsec for the (102) plane and 356 arcsec for the (002) plane. Field emission scanning electron microscopy (FESEM) verified the layer thickness and confirmed a crack-free surface, demonstrating the feasibility of thick GaN growth on sapphire for high-voltage applications.

GR-Tue-P16* - Developing GaN HEMTs Reclaiming Process for GaN on SiC Epi-Structure to Close the Loop of Supply Chain

1. Growth

Ding-Yuan Chen[1]
David Dai[1], Galia Pozina[1], Anders Lundskog[1], Jr-Tai Chen[1]
[1] SweGaN AB, IMA 1, Pursergatan 1, 58278 Linköping, Sweden

Abstract text: The increasing demand for GaN high electron mobility transistors (GaN HEMTs) in high-frequency and high-power applications has made semi-insulating SiC substrates (SI-SiC) a critical strategic material in the global semiconductor industry [1]. However, the limited availability of SiC substrates, combined with geopolitical tensions, has exposed the vulnerability of relying on a small number of suppliers for the entire supply chain.

This work introduces a novel GaN HEMT reclamation process designed to recycle SiC substrates from failed GaN-on-SiC epi-wafers using in-situ MOCVD HCl etching [2]. The proposed process involves the precise removal of HEMT layers, including the AlGaN barrier, GaN channel/buffer, and AlN nucleation layer, while preserving the quality of the underlying SiC substrate to meet epitaxy-ready standards for reuse. Comprehensive characterization methods,
such as high-resolution X-ray diffraction (HR-XRD), optical microscope (OM), atomic force microscopy (AFM), and inductively coupled plasma mass spectrometry (ICP-MS), were employed to evaluate the quality of the reclaimed SiC.

This work provides a sustainable approach to ensuring the continuity of GaN HEMT production while mitigating environmental impacts and reducing geopolitical risks. Furthermore, this process represents a significant step toward closing the loop in the GaN-on-SiC supply chain [3].

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GR-Tue-P17 - Development of gallium oxide-GaN junctions by HVPE for high-power and high-frequency electronics

1. Growth
Carl Hemmingsson[1]
Natalia Abrikossova[1], Galia Pozina[1]
[1] Linköping University, Department of Physics, Chemistry and Biology (IFM), Linköping, Sweden

Abstract text: The exceptional material properties of III-nitride compound semiconductors make them crucial for next-generation semiconductor electronics. GaN has already demonstrated its potential in optoelectronic applications such as LEDs, lasers, and optical detectors. More recently, GaN-based high electron mobility transistors (HEMTs) have gained significant interest for high-power radar systems, satellite communications, 5G infrastructure, and RF systems—applications where efficiency, reliability, and thermal stability are essential.

To further enhance device performance, the integration of κ-phase Ga_2O_3 with GaN has emerged as a promising approach. κ-Ga_2O_3 exhibits an ultra-wide bandgap of 4.7-4.9 eV and strong spontaneous polarization of 0.23 C/m^2, making it an excellent candidate for next-generation power and RF electronics. Its high critical electric field and unique dielectric properties can significantly improve device efficiency and breakdown voltage. Additionally, integrating a polar gate dielectric such as orthorhombic κ-Ga_2O_3 with GaN HEMTs can potentially enhance both the sheet resistance of the two-dimensional electron gas (2DEG) channel and the field distribution between the gate and drain [1].

We have previously developed GaN and β-phase Ga_2O_3 growth by Hydride Vapor Phase Epitaxy (HVPE), including doping studies [2]. Here, we report the successful growth of κ-phase Ga_2O_3, on sapphire (0001) and progress in fabricating κ-Ga_2O_3/GaN junctions. The structural and optical properties of the grown layers have been characterized using X-ray diffraction, scanning electron microscopy, and optical spectroscopy.

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GR-Tue-P18* - Development of GaN Micro-Pyramids and Platelets with High Uniformity for Red Emissions

1. Growth

Changhao Li[1]
Vitaly Zubialevich[1], Peter Parbrook[1], Brian Corbett[1], Zhi Li[1]
[1] Tyndall National Institute, University College Cork, Cork, Ireland

Abstract text: GaN-based red micro-light-emitting diodes (micro-LEDs) are considered as promising candidates for high performance micro-displays, due to their potential high efficiencies at small sizes compared to the counterparts (i.e. AlGaInP-based red LEDs). In terms of epitaxy, comparing with that on planar substrates, growth of micro-pyramids or platelets by the selective area growth (SAG) technique, offers a promising solution to overcome some material challenges such as reducing the lattice mismatch induced strain and the quantum-confined Stark effect (QCSE), and avoiding the sidewall damages from the dry etch. However, the size non-uniformity of these pyramids or platelets remains a significant challenge, which hinders the further development of high uniform and high efficiency red LEDs. This work first investigates the mechanisms of the size non-uniformity during the SAG process, and then optimizes the growth conditions, such as growth temperature and carrier gas ratios, to obtain uniform GaN pyramids/platelets. Finally, the InGaN quantum wells (QWs) grown on the pyramids/platelets were studied to achieved green and red emission.

By examining two different types of templates, we revealed that faster grown platelets are associated with the screw dislocations in the growth windows from the templates. This is further supported by atomic force microscopy (AFM) images taken from the tops of the platelets, showing the spiral growth around the screw dislocations for the taller platelets while step-flow growth for the shorter platelets.

To obtain uniform GaN pyramids/platelets, we demonstrated that a low growth temperature in pure H_2, or using pure N_2 as carrier gas is required, with more lateral growth observed in N_2. And uniform GaN pyramids can be achieved through a multi-step growth-then-anneal process.

Following these optimizations, InGaN QWs targeting at green and red emissions were introduced on the micro-pyramids by adjusting QW thickness, V/III ratios and barrier growth temperature. And the optical properties were characterised in detail and analysed.

GR-Tue-P19* - Enhanced GaN coalescence overgrowth on top-down nanowires using In as surfactant

1. Growth

Jingxuan Kang[1]
Huaide Zhang[1], Oliver Brandt[1], Lutz Geelhaar[1]
[1] Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., Hausvogteiplatz 5–7, 10117 Berlin, Germany

Abstract text: The coalescence overgrowth of nanowires is a promising strategy for the fabrication of group-III nitride pseudosubstrates, reducing dislocation density and alleviating lattice-mismatch-induced strain. However, compared to conventional planar epitaxy, this overgrowth typically yields rougher surfaces, limiting device structure growth on top.

In this work, we investigate the use of In as a surfactant for the coalescence overgrowth of GaN on top-down GaN nanowire ensembles. Before the overgrowth by molecular beam epitaxy, GaN nanowires were prepared via a metal dewetting patterning approach from commercial c-plane GaN templates. This patterning method is cost-effective and scalable, which is attractive for the coalescence overgrowth of entire wafers. GaN coalescence overgrowth was performed under Ga-rich conditions at 690 °C. These growth conditions lead to the formation of a continuous GaN layer with a thickness about 900 nm above the nanowires. However, the resulting samples exhibited very rough surfaces including voids and pits.

To address this limitation, In was introduced as a surfactant to enhance Ga adatom mobility during overgrowth, thus facilitating coalescence. The In flux was adjusted to ensure the formation of a stable surface adlayer, as confirmed by reflection high-energy electron diffraction. Characterization by scanning electron microscopy and atomic force microscopy showed a substantial improvement in the surface morphology. Specifically, the root mean square roughness was more than halved and the number of pits and voids strongly reduced compared to the samples grown without surfactant. Additionally, high-resolution X-ray diffraction measurements indicated that the incorporation of In was below the detection limit.

In conclusion, the use of In as a surfactant during GaN coalescence overgrowth effectively enhances the surface morphology . Therefore, the combination of top-down nanowire fabrication by metal dewetting and the coalescence overgrowth enhanced by In as a surfactant presents a scalable pathway towards the production of group-III nitride pseudo-substrates.

GR-Tue-P20* - Epitaxial Growth and Characterization of N-polar InAlGaN by Plasma Assisted Molecular Beam Epitaxy

1. Growth

Md Irfan Khan[1]
Sunil Choudhary[1], Elaheh Ahmadi[1]
[1] University of California Los Angeles

Abstract text: N-polar AlGaN/GaN high electron mobility transistors (HEMTs) have demonstrated record high output power, power density, and power-added efficiency at 94 GHz [1][2]. Recently, InAlGaN quarternary alloys have emerged as a potential solution to the drawbacks of InAlN as a barrier in GaN HEMTs. Compared to InAlN, InAlGaN has shown improved miscibility, which has translated to better performance over InAlN. Furthermore, compositional control of InAlGaN allows for additional freedom in tailoring crystallographic strain, polarization, and 2DEG density in III-nitride heterostructures. In this work, we present a comprehensive study of the impact of growth condition on the epitaxy and composition of N-polar InAlGaN films grown on single crystal GaN substrates by plasma assisted molecular beam epitaxy (PAMBE). We have changed the growth temperature between 600°C - 750°C along with different Al and Ga flux ratio between 0.3 – 1.0. We have characterized these samples with atomic force microscopy (AFM), high resolution X-ray diffraction (HRXRD), reciprocal space mapping (RSM) and secondary ion mass spectroscopy (SIMS). By changing In, Al and Ga fluxes, we have obtained $In_{0.14}Al_{0.50}Ga_{0.36}N$ which is lattice matched to GaN, as confirmed by XRD RSM. These findings are promising for future studies on PAMBE-grown N-polar GaN HEMTs with InAlGaN barriers.

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GR-Tue-P21 - Epitaxy of group III nitrides on Si with Sc2O3 interlayer

1. Growth

Tomas Grinys[1]
Arūnas Kadys[1], Tadas Malinauskas[1], Augustas Vaitkevičius[1], Žydrūnas Podlipskas[1], Rimantas Gudaitis[2], Mindaugas Andrulevičius[2], Šarūnas Meškinis[2]
[1] Institute of Photonics and Nanotechnology, Vilnius University, Vilnius, Lithuania
[2] Institute of Material Science, Kaunas University of Technology, Kaunas, Lithuania

Abstract text: The research shows that the direct epitaxy of group III nitrides on Si fails due to large thermal and lattice mismatch. One possibility of integrating such nitrides into Si technology could be heteroepitaxial growth using group III dielectrics such as scandium oxide (Sc2O3) as a buffer. Our calculations showed that the lattice mismatch between wurtzite GaN(0001) and cubic Sc2O3(111) is 8.3%, while InN(0001) and cubic Sc2O3(111) is only 1.6%. Sc2O3 has a large band gap (5-6 eV) and a high dielectric constant (ε=13). These above-mentioned properties of scandium oxide are favorable for GaN integration into silicon-based technology.
In this work, Si (111) substrates were overgrown with a 40 nm-thick Sc2O3 (111) buffer layer by molecular beam epitaxy. Afterward, a close-coupled showerhead metalorganic chemical vapor deposition reactor was used to grow GaN or InN on top of these templates.
The XRD measurements showed that single crystalline wurtzite layers of InN or GaN were grown with a relationship InN(0001) or GaN(0001)||Sc2O3(111). The crystalline quality of the layers varied depending on growth parameters such as nitridation time, growth temperature, and film thickness. In-situ reflectometer measurements showed that nucleation of InN starts with 2D layer-by-layer growth mode. Such growth mode continues up to the thickness of around 30 nm, and then the growth mode transforms to 3D growth.
The micro-stripe formation was observed when the growth of GaN up to 500 nm thick was conducted in a nitrogen atmosphere, with the stripes completely disappearing when the growth atmosphere was switched to hydrogen. The stripes were determined to be of a zincblende GaN phase. The epitaxial relationships between the zincblende GaN, wurtzite GaN, Sc2O3, and Si were examined in detail. Switching the growth atmosphere from N2 to H2 led to reduced dislocation densities, minimized zincblende GaN formation, and improved the surface morphology of the GaN layers. Our analysis shows that due to the lattice and thermal mismatch between GaN and the Si substrate, the GaN layers experience tensile strain. AlxGa1−xN interlayers were inserted after 100 nm of GaN growth to manage this strain. This strain-engineering approach resulted in smooth, crack-free GaN epitaxial layers, demonstrating the potential for integrating GaN into silicon technology using a Sc2O3.

GR-Tue-P22* - GaN nanowires grown by PAMBE on metallic ZrN buffers – a critical impact of ZrN layer thickness on the growth temperature

1. Growth

Karol Olszewski[1]
Zbigniew Zytkiewicz[1], Aleksandra Wierzbicka[1], Marek Guziewicz[2], Marta Sobanska[1]
[1] Institute of Physics, Polish Academy of Scinences, Warsaw, Poland
[2] Łukasiewicz Research Network, Institute for Microelectronics and Photonics, Warsaw, Poland

Abstract text: GaN nanowires (NWs) are typically grown by MBE on Si substrates. However, a strong absorption of light by Si substrate and nonlinear GaN/Si electrical contact create problems in optoelectronic applications. By using a nucleation layer that is electrically conductive, forms an ohmic contact to GaN and reflects back the light emitted by NW structure, the efficiency of NW-based optoelectronic devices should be significantly enhanced. To achieve this we use layers of metallic ZrN for growth of GaN NWs by plasma assisted MBE. We have reported already, that due to geometrical selection mechanism device-relevant arrays of vertical GaN NWs can be grown on polycrystalline ZrN buffers by MBE [1]. Moreover, low resistivity and an ohmic electrical contact of GaN NWs to ZrN have been observed [2].

In this work we show that presence of thin ZrN layer significantly affects substrate temperature during MBE growth: at ~830°C a 40 nm thick ZrN buffer partly covering Si substrate increased its temperature by as much as 17°C, which critically affected the NW incubation time and thus the dimensions and density of the NWs. Moreover, for the same heater power changing thickness of the ZrN layer changed optical pyrometer reading of the substrate temperature indicating thickness-dependent emissivity of ZrN/Si and ZrN/Al_2O_3 substrates. To quantify the effect we used melting of Al wires bonded to the surface of ZrN to determine emissivity of ZrN/Si and ZrN/Al_2O_3 substrates and obtain true temperature readings. We found that emissivity of ZrN films differs significantly from the bulk material and increases drastically for films thinner than ~100 nm, which agrees with theoretical predictions. This indicates that using bulk ZrN emissivity values and disregarding the influence of the thin film may lead to significant errors in the substrate temperature measurement and consequently to the loss of control of the growth process. Finally, we show that our procedure allows to compensate for the impact of ZrN on the substrate temperature and to grow identical GaN NWs on Si substrates with and without ZrN layers.

This work was supported by the Polish NCN grants 2021/43/D/ST7/01936 and 2022/04/Y/ST7/00043 (Weave-Unisono). The authors thank T. Wojciechowski for SEM measurements.

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GR-Tue-P23 - High rate, high quality tuneable nitrides by plasma atomic layer deposition enabling volume manufacturing for GaN device integration

1. Growth

Michael Powell[1]
Aileen O'Mahony[1], Elliot Gay[1], Dmytro Besprozvannyy[1]
[1] Oxford Instruments Plasma Technology, Govier Way, Western Approach Distribution Park, Severn Beach, Bristol, BS35 4GG, United Kingdom

Abstract text: GaN has been used in light emitting diodes and has expanded into power electronics, RF, microLEDs and VCSELs markets. The adoption of GaN transistors in high volume consumer-based power electronics has been driven by the need for smaller, faster, efficient mobile device chargers. It is predicted the GaN power device market will reach $2B by 2027 supported by a broader range of applications including renewable energy, data centres, electric vehicles, and infrastructure for 5G and 6G networks. These emerging GaN markets require uniform, conformal, low damage plasma processing solutions optimised for 200 mm wafers to improve device performance, throughput, and yield at reduced cost.

Plasma enhanced atomic layer deposition (PEALD) has been implemented in GaN transistors for low damage, uniform passivation layers (Al_2O_3, SiO_2, SiN), as a method of interface optimisation using plasma pre-treatments to deposit high quality nitrides such as epitaxial AlN. The need for tunability of ALD nitride processes has been demonstrated in the selective deposition of crystalline and amorphous AlN films in a single GaN transistor to increase the 2DEG carrier density and reduce the current collapse in GaN transistors resulting in faster switching, more efficient devices. High throughput plasma ALD of SiN deposition is advantageous for GaN device processing at low temperature (≤500 °C) - compared to LPCVD (usually ≥700 °C) and thermal ALD (typically >450 °C) - without compromising on conformality or uniformity up to 200 mm wafer size. PEALD SiN has also been shown to reduce trap defect density in GaN transistors compared to other deposition methods and materials. Optimisation of the plasma processing parameters can achieve SiN films with tuneable growth rate, composition and refractive index.

PEALD AlN and SiN processes were developed achieving thickness non-uniformities of 2.0% and 3.0% respectively across 200 mm Si wafers. The composition of the AlN films was measured by XPS resulting in stochiometric films with low contamination. Low HF etch rates of the deposited SiN films demonstrated high density and low contamination confirmed by refractive index. To demonstrate the tunability crystallinity of the PEALD AlN process, XRD was used to measure thicker AlN films. The AlN and SiN processes developed demonstrate high deposition rates combined with excellent film quality.

GR-Tue-P24* - High-Rate GaN Growth by Magnetron Sputter Epitaxy Using a Solid Ga Target

1. Growth

Morris Ott[1]
Hagen Bartzsch[1], Elizabeth van Hauff[1], Agne Zuskauskaite[2], Valentin Garbe[1]
[1] Fraunhofer Institute for Electron Beam and Plasma Technology, Dresden, Germany
[2] Technical University Dresden, Dresden, Germany

Abstract text: Typically, group-III nitride growth relies on established methods such as metal-organic chemical vapor deposition (MOCVD) that can be used to produce high-quality films, but requires elevated growth temperatures and use of toxic precursor gases. To address these limitations and meet the growing demand for GaN epitaxial layers, alternative deposition techniques have gained attention. One of them is magnetron sputter epitaxy (MSE). This technique offers several advantages over conventional growth processes, including sustainability, lower operating costs, easier scalability and higher throughput. A significant portion of previous research in MSE of GaN has focused on the use of liquid Ga targets.[1] Those studies have reported that liquid targets can cause particle bursts towards the substrate, potentially affecting crystal quality and uniformity. Additionally, liquid targets may require maintenance after each deposition cycle before initiating subsequent coating processes. Recently, solid Ga targets have been shown to overcome these challenges on a lab scale and produce high quality GaN.[2] The next crucial step in advancing the GaN MSE technology is scaling up. This transition necessitates the use of a fully controlled and stable sputtering process, which ensures a reproduceable and homogeneous growth of epitaxial GaN on industry-relevant substrate sizes.

In this contribution we present our latest achievements of high-rate GaN(0001) MSE on sapphire Al_2O_3(0001) substrates using Double Ring Magnetron (DRM) developed by Fraunhofer FEP. DRM was modified for sputtering a solid Ø144 mm Ga target kept at -35°C during deposition process. The technology enables a bipolar/unipolar pulsed DC sputtering in the transition region between metallic and reactive mode, referred to as controlled reactive magnetron sputtering. This allows a process window with less kinetic energy bombardment of the substrate, resulting in improved film quality while maintaining high growth rates >1 nm/s. An in-depth analysis of the grown GaN layers reveals that homogeneous film thickness and crystalline quality (ω-FWHM 0,46° and 0,67° for the 00.2 and 10.1 reflection) and smooth topography (RMS 3.7 nm) can be achieved by precise process control.

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GR-Tue-P25* - Impact of AlN Buffer Thickness on the 2DEG and Thermal Properties of thin-GaN channel HEMTs

1. Growth

Minho Kim[1]
Dat Q. Tran[2], Plamen P. Paskov[2], Vallery Stanishev[3], Okhyun Nam[4], Vanya Darakchieva[5]
[1] Wallenberg Initiative Materials Science for Sustainability (WISE), Department of Physics, Chemistry and Biology (IFM), Linköping University, Linköping, Sweden
[2] Center for III-Nitride Technology, C3NiT-Janzén, Linköping University, Linköping, Sweden
[3] Center for III-Nitride Technology, C3NiT-Janzén, Linköping University, Linköping, Sweden and NanoLund and Lund University, Lund, Sweden
[4] Convergence Center for Advanced Nano Semiconductor (CANS), Department of Nano-Semiconductor, Tech University of Korea, Siheung-si, Republic of Korea
[5] Wallenberg Initiative Materials Science for Sustainability (WISE), Department of Physics, Chemistry and Biology (IFM), Linköping University, Linköping, Sweden, Lund University, Lund Sweden and Terahertz Materials Analysis Center, THeMAC, Lund University, Lund, Sweden

Abstract text: III-N HEMTs with AlGaN/GaN/AlN double-heterostructures show strong potential for power and RF applications, leveraging AlN's wide bandgap (6.1 eV), high thermal conductivity (340 W/mK), and buffer layer effectiveness. The AlN buffer enhances 2DEG confinement, supports high breakdown voltages, and mitigates buffer traps common in carbon- or iron-doped substrates. It also aids strain relaxation, defect reduction, and thermal dissipation, preserving GaN channel quality and 2DEG mobility. However, optimizing AlN buffer thickness is challenging due to thermal expansion mismatches and lattice strain, which can cause defects and cracking. Thin buffers fail to relieve strain, increasing defect density and thermal resistance, while thick buffers risk cracking and growth issues, affecting device reliability.[1][2]

This study explores how AlN buffer thickness (120 nm to 2 μm) affects the structural, 2DEG and thermal properties of 150-nm GaN channel HEMTs grown on semi-insulating SiC. Our goal is to optimize buffer design for improved device stability, performance, and efficiency in high-power applications. Mobility measurements show that the 2-μm AlN buffer HEMTs yields 2DEG mobility of 1460 $cm^2/(V \cdot s)$ at room temperature and 7100 $cm^2/(V \cdot s)$ at 70K, while the 120-nm buffer achieves 1550 $cm^2/(V \cdot s)$ at room temperature and 8770 $cm^2/(V \cdot s)$ at low temperature. Thermal transport analysis, incorporating experimental thermal conductivity measurements and electro-thermal simulations, reveals a 14% reduction in surface temperature for devices with thicker AlN buffers. This result is attributed to the higher thermal conductivity of thicker AlN buffer layers, primarily due to reduced phonon boundary scattering. These findings underscore the potential of AlN-buffered HEMTs to enhance efficiency and performance in high-power, high-frequency applications.

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GR-Tue-P26 - In-situ MOCVD Doping of Be and Be,O in (Al,Ga)N for Improved p-Type Conductivity

1. Growth

Fatemeh (Shadi) Shahedipour-Sandvik[1]
Benjamin McEwen[2], Ronak Safari[2], Alireza Lanjani[2], Denis Demchenko[3], Michael Reshchikov[3]
[1] United States
[2] SUNY Albany, Albany, New York, USA
[3] Virginia Commonwealth University, Richmond, Virginia, USA

Abstract text: Ultra-wide bandgap (UWBG) $Al_xGa_{1-x}N$ is a key material for next-generation high-power and optoelectronic devices due in main part to its tunable bandgap (~3.4 eV to ~6.1 eV). However, achieving efficient p-type conductivity remains a critical challenge, as Mg—the only widely used acceptor in III-nitrides—has a high activation energy, particularly in Al-rich compositions, which severely limits hole conduction. Alternative acceptors and doping strategies are therefore needed to advance UWBG device performance.

Beryllium (Be) has emerged as a promising alternative due to its shallower acceptor level (~0.33 eV in AlN, ~0.113 eV in GaN), potentially leading to higher hole activation in these materials. However, experimental studies so far have revealed that Be-doped III-nitrides often exhibit semi-insulating behavior, suggesting a complex acceptor nature [1]. Recent first-principles calculations have identified the $Be_{Ga}O_NBe_{Ga}$ complex as the likely origin of the Be-related ultraviolet luminescence (UVL_{Be}) band at 3.38 eV, pointing to its role as the shallowest acceptor in GaN.

In this work, we systematically investigate the in situ incorporation of Be, and co-doped Be,O in (Al,Ga)N grown by metal-organic chemical vapor deposition (MOCVD). We optimize growth conditions—including precursor flow, V/III ratio, and pressure—to maximize Be incorporation while preserving high material quality. Advanced characterization techniques, including SIMS, AFM, XRD, PL and TEM are employed to assess doping efficiency, structural integrity, and defect formation.

Our findings provide a deeper understanding of Be as a p-type dopant in (Al,Ga)N, bridging experimental data with theoretical models. This work lays the foundation for improved p-type doping strategies in UWBG III-nitride semiconductors.

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GR-Tue-P27 - Mechanism of self-assembled cubic InGaN/GaN quantum wells and bulk InGaN layers in metal-modulated molecular beam epitaxy

1. Growth

Mario F. Zscherp[1]
Silas A. Jentsch[1], Vitalii Lider[2], Matthew Chia[3], Markus Stein[1], Andreas Beyer[2], Anja Henss[1], Donat J. As[4], Kerstin Volz[2], Sangam Chatterjee[1], Jörg Schörmann[1]
[1] Institute of Experimental Physics I and Center for Materials Research, Justus Liebig University Giessen, Giessen, Germany
[2] Materials Science Center and Faculty of Physics, Philipps-University Marburg, Marburg, Germany
[3] Department of Physics, Cambridge University, Cambridge, United Kingdom
[4] Department of Physics, Paderborn University, Paderborn, Germany

Abstract text: Cubic $In_xGa_{1-x}N$ alloys hold significant promise as active materials for next-generation optoelectronic devices, including red micro light-emitting diodes (µ-LEDs). Their successful application requires precise engineering of quantum structures, particularly focusing on parameters such as the widths of quantum wells, strain, and indium content. In this context, we employ a metal-modulated growth scheme where gallium and indium sources are shuttered individually, leading to the formation of self-assembled c-$In_xGa_{1-x}N$/GaN quantum well structures with distinct interfaces [1]. Furthermore, the same growth scheme can yield fully alloyed bulk c-InGaN layers even though gallium and indium are never supplied simultaneously.

We discuss the underlying physical phenomena enabling the self-assembled formation of cubic $In_xGa_{1-x}N$/GaN quantum wells on c-GaN/AlN/3C-SiC/Si templates using molecular beam epitaxy (MBE). *In situ* analysis is conducted via reflection high-energy electron diffraction (RHEED), and the layers are thoroughly characterized using scanning transmission electron microscopy (STEM), time-of-flight secondary-ion mass spectrometry (ToF-SIMS), and high-resolution X-ray diffraction (HRXRD). Our results show that indium does not incorporate into the underlying c-GaN layer and binary c-InN formation is excluded at the chosen growth temperature. Instead, indium accumulates on the surface, leading to the formation of c-$In_xGa_{1-x}N$ during subsequent GaN cycles until the indium reservoir is consumed. This process is attributed to vertical cation segregation [2], enabling a thermodynamically stable $In_xGa_{1-x}N$ stoichiometry at the metal-crystal interface. The indium content is closely tied to the substrate temperature, and we discuss both the limitations and applicable composition range for this growth method of cubic InGaN. Photoluminescence studies reveal the impact of quantum well structures, indium content and strain on the optical response.

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GR-Tue-P28 - MOVPE Growth Dynamics of GaN on High-Resistivity Si and SOI Substrates

1. Growth

Ramesh Raju[1]
Maria Golovleva[2], Heikki Holmberg[2], Ilkka Tittonen[1]
[1] Department of Electronics and Nanoengineering, Aalto University, P O BOX 13500, FI-00076 AALTO, Finland
[2] Okmetic Oyj, Piitie 2, FI-01510 Vantaa, Koivuhaka, Finland

Abstract text: Gallium Nitride (GaN) is an essential material for high-power and high-frequency applications due to its wide bandgap, high electron mobility, and excellent thermal stability. Metal-Organic Vapor Phase Epitaxy (MOVPE) remains the preferred method for GaN growth, enabling precise control over layer composition and thickness. However, substrate selection plays a crucial role in determining the quality and properties of GaN films. In this study, we examine GaN growth on both Silicon (Si) and Silicon-on-Insulator (SOI) substrates using MOVPE, focusing on their structural and electrical characteristics.

We conduct a comparative analysis of GaN films grown on high-resistivity Si and SOI substrates with different Buried Oxide (BOX) thicknesses and off-cut angles. Our study utilizes 150 mm diameter high-resistivity silicon and SOI wafers featuring a 2 μm buried oxide layer. The handle silicon in SOI samples exhibits a resistivity greater than 5000 Ω.cm.The off-cut angles of the substrates are 0° and 0.35°, which influence step-flow growth dynamics and defect reduction. We analyze the impact of substrate choice and off-cut angle on GaN epitaxial layer quality, defect density, and electrical performance.

Our key findings highlight the influence of substrate resistivity, BOX thickness, and off-cut angle on strain distribution, dislocation density, and interface integrity. The results suggest that SOI substrates provide advantages in managing thermal stress and enhancing device performance compared to bulk silicon. These insights are crucial for advancing GaN-based power electronics and RF applications, paving the way for improved device reliability and efficiency.

GR-Tue-P29 - Microstructure control of zincblende GaN via nucleation layer growth V-to-III ratio

1. Growth

MJ Kappers[1]
M Frentrup[1], DJ Wallis[2], RA Oliver[1]
[1] Department of Materials Science and Metallurgy, University of Cambridge, UK
[2] Centre for High Frequency Engineering, Cardiff University, Cardiff, UK

Abstract text: The development of zincblende (zb) GaN films is demanding due to its metastable nature leading to wurtzite inclusions and a high density of {111} type stacking faults (SFs) that may negatively influence the films' optical and electrical properties.

Our goal was to investigate the effect of the growth conditions of a low-temperature GaN nucleation layer (NL) on the microstructure and phase purity of the subsequently grown high-temperature GaN epilayer. The zb films were grown by MOVPE on 3C-SiC/ Si(001) substrates. In particular, the NL V-to-III ratio was varied for (i) a series of ~200nm-thick NL analogue samples and (ii) a series of samples with a ~40nm-thick NL plus a ~650nm-thick epilayer grown under constant reactor conditions. The samples of the two series were investigated in detail using high resolution X-ray reciprocal space maps (RSMs).

It was found that the phase purity and microstructure of the zb GaN epilayers were substantially changed by varying the NL V-to-III ratio. The RSMs measured in the [110] crystallographic direction and probing {111} planes with Ga-polarity showed an opposite trend with changing NL V-to-III ratio compared to the [1-10] direction with N-polar {111} planes. For instance, at low NL growth V-to-III ratio values, wz inclusions formed on {111} Ga-polar planes but not on {111} N-polar planes. In contrast, at high NL growth V-to-III ratio values, wz inclusions on {111} N-polar planes were observed but not on {111} Ga-polar planes.

The X-ray RSMs of the thick NL analogue sample series showed the same trend with changing NL growth V-to-III ratio as the epilayer sample series. This indicates that planar defects formed in the NL determine the microstructure in the epilayer grown on top. However, clear wz reflections were absent from the RSMs of the thick NL samples suggesting that (i) SFs in the NL develop into wz inclusions during epilayer growth OR (ii) small amounts of wz phase in NL are below XRD detection limit OR (iii) changes of NL surface morphology with V-to-III ratio determine the in-plane distribution of wz inclusions.

Hence, the suppression of SFs and/or wz inclusions along {111} planes with either Ga- or N-polarity can be achieved with a sensible choice of NL growth V-to-III ratio. These and other details will be discussed concerning our understanding of MOVPE-grown zb GaN films on 3C-SiC/Si(001) substrates.

GR-Tue-P30* - Novel solutions for the deposition of highly n-doped GaN by sputtering

1. Growth

Thomas Tschirky[1]
Marco Rechsteiner[1], Mohamed Elghazzali[1], Philipp Döring[2], **Silvia Schwyn Thöny**[1]
[1] Evatec AG, Trübbach, Switzerland
[2] Fraunhofer Institute for Applied Solid State Physics (IAF), Freiburg, Germany

Abstract text: Magnetron sputter epitaxy of GaN has the potential to produce high quality layers at lower temperatures with higher throughputs at a fraction of the cost of both MOCVD and MBE. Some remarkable results have already been demonstrated, such as tunnel junction contacts in UV-A light emitting diodes [1] and $Al_{0.5}Ga_{0.5}N$ high electron mobility transistors with selectively regrown, heavily Si-doped GaN contacts [2]. The development of advanced GaN-device contact processes is currently driven in large part by such n-GaN regrowth methods, especially for use with highly-scaled AlGaN or novel Al(Sc)N-based HEMTs with high Al-content. Highly n-doped GaN contacts would facilitate a current transport mechanism completely determined by tunnelling through the potential barrier at the metal-semiconductor interface to achieve the lowest possible contact resistance.

Our previous results have already demonstrated low specific resistivities of GaN layers produced with a non-uniform doping method [3]. In this work, sputtered GaN layers with a more uniform Si-doping method are presented, and the electron transport properties are investigated. The layers were deposited in prototype magnetron sputtering chambers based on Evatec Clusterline® 200 modules, capable of depositing GaN layers on wafers up to 8" in size.

Extremely high donor concentrations above 3×10^{20} cm^{-3} at low process temperatures (<800°C) with specific resistivities as low as 420μΩcm were achieved for layers even thinner than 100nm grown homoepitaxially on GaN templates. Good results have also been achieved by growing directly on sapphire substrates and SiC substrates. Whereas growth on SiC substrates achieved similar carrier mobilities and densities as on GaN, carrier mobilities in layers sputtered directly on sapphire substrates degrade especially for thin GaN layers.

Process and hardware development is ongoing to achieve the best conducting sputtered GaN layers and ultimately lowered contact resistances to GaN devices. Already these results demonstrate the feasibility of sputtered GaN as an alternative process with high carrier density and easy upscaling suitable for future process integration into future GaN-based devices.

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GR-Tue-P31* - N-polar GaN growth via high temperature chlorine-based halide vapor phase epitaxy for rapid dislocation reduction

1. Growth

Ping Qiu[1]
Keito Shiroma[1], Kota Nemoto[1], Hisashi Murakami[1]
[1] Graduate School of Bio-Applications and Systems Engineering (BASE),Tokyo University of Agriculture and Technology, Tokyo, Japan

Abstract text: High-quality single-crystal substrates with extremely low threading dislocation density (TDD) are required to fabricate high-performance power devices. The conventional method for GaN substrates already in mass production is the HVPE method, and the reduction of the TDD is being investigated [1]. Since the growth temperature of HVPE is typically at around 1000 °C, growth of thick GaN crystals via Cl_2-based HVPE using GaCl and NH_3 at fairly high temperatures above 1300 ℃ is investigated. Here, we propose Cl_2-based HVPE effectively enlarges the crystal diameter and improves the crystalline quality [2].

First, it was found that the GaN grown directly on sapphire at 1350 ℃ showed N-polarity, which could lead to crystal enlargement, confirmed by the hexagonal hillocks observed after KOH etching. Next, we conducted the homoepitaxial growth on GaN substrate at 1300-1350 ℃to investigate the inclination angle of threading dislocations from the c-axis. The distribution of inclination angles covered a wide range from 0 to 25°, whereas in conventional HVPE, they typically range from 0 to 4°, with a smaller proportion between 4 and 11° [3]. This result suggests that high-temperature conditions of the Cl_2-based HVPE enhance the precursor migration on growing surface, which in turn promotes two-dimensional growth and increases the inclination angles of dislocations. Therefore, it is expected that the dislocations can be annihilated more rapidly than conventional HVPE. Thus, we performed the experiments on GaN/sapphire template at 1325 and 1350 ℃. The TDD of the template was about 10^9 cm^{-2} and the TDDs were reduced to about 3.0×10^7 cm^{-2} when the film thickness was only 45 μm at 1350 ℃. Because the TDD could be reduced to about 4.0×10^7 cm^{-2} at the thickness of 100 μm in conventional HVPE [4], high-temperature growth was quite effective to reduce dislocations.

Finally, we obtained a high-quality thick GaN layer over 300 μm at 1350 ℃ using Cl_2-based HVPE method. The TDD was significantly reduced to 7.3×10^5 cm^{-2} and we achieved a maximum growth rate of 173 μm/h.

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GR-Tue-P32 - RF-MBE growth and characterization of InAlN thermoelectric thin films

1. Growth

Momoko Deura[1]
Shota Hattori[2], Tsutomu Araki[2]
[1] School of Fundamental Science and Engineering, Waseda University, Japan
[2] College of Science and Engineering, Ritsumeikan University, Japan

Abstract text: Some studies on the thermoelectric (TE) properties of nitride semiconductors have been reported. However, the elucidation of TE properties is insufficient because the growth of high-quality nitride films, in particular, InN-related alloys is highly challenging. In this study, we investigated the conditions to grow high-quality ≥100 nm-thick InAlN films using RF-MBE, which is advantageous for the InN growth, as well as to evaluate their TE properties.

On c-plane GaN (~2 μm)/sapphire template substrates, a ~10-nm-thick GaN buffer layer followed by the undoped InAlN film was grown. In typical RF-MBE of nitrides, III/V ratio≥1 (slightly metal-rich) is preferable, and the optimum growth temperature of ternary alloy is between those of two binary materials. When these growth conditions were applied to InAlN, In-rich InAlN polycrystals coexisted with the epitaxial InAlN film. This was induced by phase separation (PS) owing to a strong immiscibility of InAlN. Furthermore, Al atoms instantaneously agglomerated on the surface because the Al melting point (660 °C) is higher than the growth temperature (~500 °C), which became the origin of polycrystals. Therefore, the growth was performed under the III/V ratio<1 and at lower temperature than that of InN (435 °C). A flat and singly oriented InAlN film of the single In content of ~25% without PS was grown. However, when the thickness was increased to ~80 nm to ~180 nm, cracks (CR) appeared because of the tensile strain generated during the coalescence of columnar grains.

The Seebeck coefficients S of InAlN films with and without PS and CR were evaluated. The In content was constant to ~25%. All films showed negative value of S, indicating an n-type. $|S|$ without PS was over 300 μV/K regardless of CR, because the sum of $|S|$ of each region divided by CR was observed. In contrast, $|S|$ with PS decreased maybe owing to high carrier concentration induced by defects. It is possible to suppress the decrease in $|S|$ by controlling the structure of the film/PS interfaces. Moreover, it is also expected that PS reduces thermal conductivity.

We thank Prof. Yoshiaki Nakamura and Lect. Takafumi Ishibe of Osaka University for their help with the evaluation of the TE properties. This study was partly supported by JSPS KAKENHI 23K26148 and the Toyota Physical and Chemical Research Institute Scholar Joint Research Program.

GR-Tue-P33* - Selective area growth of GaN micro-platelets on graphene for micro-LEDs applications

1. Growth

Jonathan Henriques[1]
Dyhia Tamsaout[2], Ludovic Largeau[2], Edmond Cambril[2], Gwénolé Jacopin[3], Maria Tchernycheva[2], Jean-Christophe Harmand[2], Joël Eymery[4], Christophe Durand[1]
[1] Université Grenoble Alpes, CEA, Grenoble-INP, IRIG, PHELIQS, NPSC, 38000 Grenoble, France
[2] Centre de Nanoscience et Nanotechnologie (C2N), CNRS, Université Paris-Saclay, 91120 Palaiseau, France
[3] Université Grenoble Alpes, Grenoble-INP, CNRS, Institut Néel, 38000 Grenoble, France
[4] Université Grenoble Alpes, CEA, IRIG, MEM, NRX, 38000 Grenoble, France

Abstract text: Growth on 2D materials such as graphene holds great promise thanks to Van der Waals bonds that enable easy detachment for the development of flexible µLEDs. However, the low binding and surface energies make nucleation on such 2D material challenging and an AlGaN or AlN interlayers is required to promote nucleation. To solve this issue, the selective growth of N-polar nanowires (NWs) by MBE on organized graphene patches on a SiO_2/Si substrate has been demonstrated recently.[1–3]

Using this method, we use MBE NWs as seeds to perform selective area MOVPE growth of GaN µ-platelets on hexagonal patterned graphene patches with varying spacing and radius (R).[4] The growth conditions have been chosen to promote lateral overgrowth of the NWs to form organized GaN µ-platelets. For larger radii, a higher NW number is observed within the patches, that significantly influences the selectivity overgrowth by increasing the probability of nucleation. Optical and structural characterizations exhibit the appearance of stacking faults in the lower part of the structure linked to inverted inclined facets induced by the N-polarity growth. It is shown that while the surface of the µ-platelets is free of dislocations for small R, Ga-polarity inclusions occur at their center. The growth of three InGaN/GaN quantum wells (QWs) on these N-polar GaN µ-platelets evidences an optical emission that is only observed on the m-plane facets and the Ga-polar inclusions. The emission wavelength from blue (460 nm) toward green (550 nm) showed significant variations of indium content due to different In and Ga adatom diffusion on the facets. TEM observations on the same µ-platelets confirm that the Ga-polar inclusion acts as a sink for indium adatoms, promoting a red emission around 600 nm. As a result, these µ-platelets are a first important step allowing us to imagine the growth of µLED arrays on graphene suitable for flexible applications.

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GR-Tue-P34* - Selective Area Growth of GaN Nanowires on Si with Ga Pre-Filling

1. Growth

Gulzhan Baigarinova[1]
Tron Arne Nilsen[1], Swagata Bhunia[1], Helge Weman[1], Bjørn-Ove Fimland[1]
[1] Department of Electronic Systems, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway

Abstract text: GaN-based nanowires (NWs) have emerged as key building blocks for high-efficiency optoelectronic devices, such as light-emitting diodes, laser diodes, and single-photon sources. Achieving high efficiency of those devices often demands precise location and dimensions of the NWs. The most widely used technique for achieving such controlled NW growth is the selective area growth (SAG) process. Despite tremendous research efforts, SAG growth of GaN NWs on Si substrate using SiO_2 mask remains highly challenging, due to the long incubation time of NW-nuclei on Si, parasitic growth on SiO_2 mask area, and multiple NWs growth in a single hole area. AlN has been used as a seed layer to reduce the incubation time and obtain a single hexagonal GaN NW in each hole; however, it affects the electrical properties across the substrate/NW interface [1]. In this work, by using a two-step molecular beam epitaxy growth technique, we have successfully grown NW arrays with a single GaN NW per hole in the patterned area without using any buffer layer. Furthermore, we demonstrate that our method significantly reduces the nucleation time and parasitic growth.
Before growth, hexagonal patterns of 100 nm diameter holes with center-to-center pitches ranging from 200 to 1600 nm were created using electron beam lithography on a 20 nm SiO_2 layer, deposited on Si(111) by plasma-enhanced chemical vapor deposition. In the first step of growth, at a substrate temperature of 500˚C, Ga was pre-filled in mask holes and subsequently consumed by active nitrogen, using the pulsed growth method. This step reduces the nucleation time and may also limit the Si_xN_y formation due to shorter nitrogen exposure time compared to traditional nucleation process. In the next step, the substrate temperature was raised to normal GaN growth temperatures and NWs were grown. Scanning electron microscopy (SEM) images show that the NW diameter and height remain nearly uniform across the pattern area after the two-step growth. For comparison, NWs were also grown directly on the patterned substrate in a one-step growth (i.e., without the low-temperature step). The SEM images reveal that instead of a single NW per hole, multiple uncoalesced NWs with reduced lengths were formed inside the holes.

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GR-Tue-P35 - Surface morphology of 265 nm optically pumped lasers on high temperature annealed AlN/sapphire with different miscut

1. Growth

Massimo Grigoletto[1]
Lennard Zinsilowski[2], Giulia Cardinali[2], Tim Wernicke[2], Michael Kneissl[1]
[1] Technische Universität Berlin, Institute of Solid State Physics, 10623 Berlin, Germany, Ferdinand-Braun-Institut (FBH), 12489 Berlin, Germany
[2] Technische Universität Berlin, Institute of Solid State Physics, 10623 Berlin, Germany

Abstract text: The demonstration of the first current injection UVC laser diodes grown on low dislocation bulk AlN substrates did not only prove the feasibility of these devices but also showed the detrimental impact of hexagonal hillocks on the lasing properties. The impact of surface morphology on optical gain is studied by analyzing hillock formation based on the miscut angle of HTA AlN/sapphire templates. Increasing the sapphire miscut angle significantly reduces hillock size and density. In this study, optically pumped AlGaN multiple quantum well lasers were grown by metalorganic vapor-phase epitaxy on (0001) HTA AlN/sapphire templates with a miscut angle of 0.1° and 0.5° to the m-direction. The laser heterostructure was comprised of an AlN base layer, a $Al_{0.76}Ga_{0.24}N$ cladding layer, a 50 nm $Al_{0.63}Ga_{0.37}N$ waveguide, two 4.5 nm $Al_{0.51}Ga_{0.49}N$ QWs with 5 nm $Al_{0.63}Ga_{0.37}N$ barriers, and another 50 nm $Al_{0.63}Ga_{0.37}N$ waveguide completed the structure. The surface morphology was evaluated by atomic force microscopy (AFM) and laser scanning microscopy. Optical pumping experiments utilizing variable stripe length method (VSLM) were conducted to determine the gain of the lasers. The thickness of the cladding layer was systematically varied on AlN/sapphire templates with a 0.1° offcut. In our study, samples without AlGaN cladding layer exhibited smooth, layer-by-layer growth with no hillocks and the optically pumped laser achieved a positive gain at excitation power densities of 1.5 MW/cm². For a 800 nm and 1200 nm thick cladding layer structure, the hillock density on the surface increased to 8% and 14%, respectively, alongside a higher RMS roughness (7.6 nm to 13.1 nm), requiring higher pumping powers (~10 MW/cm² and 15 MW/cm²) for positive optical gain. Lasers with an 800 nm AlGaN cladding layer grown on a 0.5° offcut substrate exhibited a combination of step-flow growth and triangular features with an RMS roughness of 1.2 nm. The elongated step structures indicated a step-flow growth mode, though with noticeable roughness, likely influenced by dislocations. These lasers achieved a net modal gain of ~40 cm^{-1} at 5 MW/cm² and positive gain at 2.1 MW/cm², outperforming a 0.1° offcut sample, which reached only ~10 cm^{-1} at 5 MW/cm². High gain was only achieved without hillocks, requiring growth on higher sapphire offcut angles.

GR-Tue-P36 - Towards true vertical GaN-on-Si(111) devices with TiN

1. Growth

Armin Dadgar[1]
Emine Kaynar[1], Fabian Großmann[1], Florian Hörich[1], Jürgen Bläsing[1], André Strittmatter[1]
[1] Intitut für Physik, Otto-von-Guericke-Universität Magdeburg, Magdeburg, Germany

Abstract text: GaN-on-Si(111) enables low-cost, high-power and high-voltage GaN electronics, typically with a lateral current flow and therefore requiring a large wafer area. Recently true vertical diodes were demonstrated in conventionally grown GaN-based structures achieving a breakdown voltage of 1200 V [1]. This was achieved by sequential removal of the Si substrate and the insulating Al-rich buffer layers. A much less demanding alternative for high-power vertical electronics on Si(111) could be established by replacing insulating AlN/AlGaN buffer structures with metallic TiN. High-quality, metallic TiN layers can be grown by reactive sputter epitaxy from a Ti target, but also by MOVPE from TiCl4 and ammonia, achieving growth rates comparable to AlN. Here, we investigate the compatibility of TiN for MOVPE growth of vertical device structures on n-Si(111) substrates aiming at a highly conductive TiN/Si hetero-interface [2]. In first MOVPE experiments, we observe difficulties to directly grow GaN on TiN due to poor wetting. This changes as soon as some Al is added to the growing GaN layer, e.g. by starting with an AlGaN:Si buffer layer on top of the TiN. So far, epitaxial sputtering of TiN yields the best crystalline quality. Depending on the TiN-on-Si surface morphology (Fig. 1) we are able to obtain GaN layers with smooth surface morphologies, comparable to GaN-on-Si growth, already at ~800 nm layer thickness. Accordingly, XRD ω-(0002) FWHM values for GaN is around 0.16 ° to 0.17 ° relatively independent of the TiN quality which yields ω-(111) FWHM values ranging from 0.13 ° to 0.56 °, respectively. The excellent XRD results for the GaN layers are obtained despite a 5.9% mismatch in atomic spacing between GaN and TiN. In contrast to our typical AlN/AlGaN buffer layers, electrical measurements performed on GaN:Si/TiN/Si(111) structures show vertical current flow confirming the principal suitability of TiN for vertical device architectures. We will present our latest results of GaN MOVPE growth on TiN including also TiAlN buffer layers and further electrical data comparing the different heterointerfaces, also in dependence of n-type doping and Al-content in the (Al)GaN buffer layers. We will also discuss the feasibility of TiAlN for strain engineering of the GaN layers grown on top.

GR-Tue-P37 - Unveiling Growth-Driven Optical Dynamics in Molecular Beam Epitaxy Grown InGaN/GaN Nanowires: A Systematic Study

1. Growth

Soumyadip Chatterjee[1]
Subhranshu Sekhar Sahu[2], Kanchan Singh Rana[1], Aasheesh Sharma[1], Umang Singh[1], Dipankar Saha[1], Apurba Laha[1]
[1] Department of Electrical Engineering, Indian Institute of Technology Bombay, India
[2] Department of Physics, Indian Institute of Technology Bombay, India

Abstract text: Molecular Beam Epitaxy (MBE) Grown InGaN/GaN-based nanowire (NW) Light-Emitting Diodes (LED) have attracted a lot of interest by enabling light emission in the entire visible wavelength, making them ideal for optoelectronic applications. However, achieving optimal device performance requires precise control over growth conditions. Despite extensive research over multiple years, a detailed understanding of how growth conditions govern emission characteristics remains an active area of investigation. To unlock the full potential of InGaN/GaN NW LEDs, it is crucial to explore the influence of growth parameters on emission dynamics and device performance.

In this work, we systematically investigate the effects of growth temperature, Indium flux, and Nitrogen plasma conditions on the optical characteristics of MBE-grown InGaN/GaN MQDs. Photoluminescence (PL) measurements demonstrate a strong dependence of the emission peak position on growth conditions. A prominent redshift of the emission peak was observed at lowered growth temperatures and increased indium flux. In contrast, Nitrogen plasma conditions exhibit a non-monotonic peak shift, indicating competing influences on Indium incorporation and strain relaxation. Low-temperature PL measurements provide further information regarding the optical performance of these structures.

Carrier lifetime analysis using time-correlated single-photon counting (TCSPC) provides insights into recombination dynamics. The faster decay component, primarily associated with non-radiative processes, shows a monotonous increase or decrease with growth conditions. In contrast, the slow decay component, associated with radiative recombination, follows a non-monotonic trend driven by strain, compositional fluctuations, and carrier localization effects.

Additionally, Raman spectroscopy was performed to investigate strain effects in the samples. The shift in A_1(LO) phonon mode provides a direct measure of residual strain, revealing a correlation between growth conditions and strain relaxation.

These findings offer critical insights into optimizing growth parameters for high-performance InGaN/GaN-based NW LEDs, advancing their potential in next-generation optoelectronic applications.

GR-Tue-P38 - Vertical nanowire-based high electron mobility transistor structure grown by MOCVD

1. Growth

Ashutosh Kumar[1]
Patrick Diehle[2], Peter Ramvall[1]
[1] RISE Research Institutes of Sweden, Scheelevägen 17, SE-223 63 Lund, Sweden
[2] Fraunhofer Institute for Microstructure of Materials and Systems (IMWS), Halle

Abstract text: The concept of GaN/AlGaN core–shell nanowires (NWs) is interesting for the realization of vertical high-electron mobility transistors (HEMTs). In a vertical device, current flows vertically or in parallel with the direction of the GaN epitaxial drift layer. Consequently, current conduction occurs through the NW channel and then through a bulk drain drift region formed by a GaN layer on a Si-doped GaN contact layer grown on a GaN on sapphire substrate. Unlike lateral devices, vertical GaN/AlGaN core–shell NW-based devices do not have a 2DEG drain drift region near the surface or a defect-rich buffer layer, as found in regular GaN HEMTs. Instead, the device benefits from the low-defect M-planes on the six sides of the NWs.

In this work an Aixtron MOCVD tool was used for growing a GaN/AlGaN core–shell NW structure on GaN by selective area growth (SAG) with about 150 nm diameter holes in a SiNx mask defined by Talbot lithography. The following growth scheme was utilized:

1. GaN NW core at 960 ºC length ~600 nm as det. by SEM
2. AlGaN NW shell at 960 ºC gas-phase 22 % Al ~12 nm as det. by EDX
3. AlN exclusion layer at 1060 ºC, ~ 1-2 nm as det. by EDX
4. AlGaN NW shell at 1060 ºC gas-phase 24 % Al ~7 nm as det. by EDX
5. GaN NW cap layer at 1060 ºC ~1-2 nm as det. by EDX

The GaN/AlGaN core–shell NW morphology after growth displays an edge-like structure at the foot of some NW, but no pronounced tapering. The NW were subsequently covered by a layer of 1200 nm Ni gate metal. Lamellas suitable for transmission electron microscopy (TEM) were prepared by focused ion beam (FIB).

The structural integrity of the GaN/AlGaN core–shell NW was very good as revealed by a TEM; no dislocations were observed in the GaN/AlGaN or at the GaN substrate/NW interface. To investigate the thickness and Al composition of the AlGaN layer energy-dispersive x-ray spectroscopy (EDX) was applied. The AlGaN shell is clearly distinguishable from the GaN core with an interface sharpness of about 1 nm. The resulting estimated thicknesses of the AlGaN shells are listed in the above growth scheme. At 1060 ºC a clear preference for growth in the axial rather than the radial direction could be observed. The Al composition of the AlGaN layer grown at 960 ºC is around the gas-phase composition at ~ 20 % while at 1060 ºC the Al incorporation is strongly dependent on the crystal orientation as determined by EDX.

PC-Tue-P1 - Identification of the Fe acceptor in semi-insulating heavily Fe doped HVPE GaN by optical studies

2. Physics and characterization

Auditee Majumder Momo[1]
Ronny Kirste[1], Chao-I Liu[1], Sanam Saeid Nahaei[2], Selim Elhadj[2], Zlatko Sitar[1], Ramón Collazo[1]
[1] Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina 27695, USA
[2] Seurat, Wilmington, MA, USA

Abstract text: GaN doped with Fe or Mn is crucial for lateral electronics and spintronics applications. HVPE facilitates rapid growth of low-impurity GaN for high-quality free-standing substrates. Unintentionally doped GaN shows n-type conductivity from Si or O impurities. In contrast, Fe doping induces semi-insulating (SI) behavior with a deep Fe^{3+} acceptor state (~0.6 eV below the conduction band) that compensates free carriers. Fe doping also increases hole traps (~0.75eV above the valence band) and electron traps (~0.45 to 1.49eV below the conduction band). In heavily Fe-doped GaN ($\geq 10^{19} cm^{-3}$), the Fermi level shifts to a position below or near the Fe^{3+} state. Thus, Fe-doped GaN exhibits both shallow (Fe^{2+}/Fe^{4+}) and deep (Fe^{3+}) states, with deep states dominating at high Fe concentrations. This study investigates a series of heavily Fe doped, SI GaN samples using PL, absorption, and Hall measurements to elucidate the coexistence of deep and shallow Fe acceptor states.

Commercially available 400µm SI Fe-doped GaN substrates were characterized with Fe concentration ranges from $1.4x10^{19} cm^{-3}$ to $3.4x10^{20} cm^{-3}$, and Si and O around $1.23x10^{17} cm^{-3}$ and $1.8x10^{16} cm^{-3}$, respectively. Temperature-dependent Hall measurement confirmed an activation energy of~0.6eV, indicating the deep Fe^{3+} acceptor state. Using a tungsten lamp at room temperature, an absorption line at 2.7eV is observed, attributed to transitions from $^4E(G)$ excited state to $^6A_1(S)$ ground state of Fe^{3+}, increased with Fe concentration, supporting the dominance of Fe^{3+} in heavily doped GaN. Additional absorption lines related to excited and ground state transitions and vacancies were observed only in the highest Fe-doped sample. The excitation of Fe^{3+} in PL involves the generation of holes in the valence band, followed by their capture, leading to high excitation efficiency near the bandgap region. This is demonstrated by fine excitonic emissions in the near-band-edge range when excited with a HeCd laser. Only the highest Fe-doped GaN showed blue luminescence near 3.00 eV, indicating DAP transitions linked to defect complexes. Photoconductivity measurements revealed no photocurrent, suggesting that the materials were fully compensated by Fe^{3+}, with no detectable Fe^{2+} states. In summary, the Fe acceptor states are identified by analyzing absorption spectra, PL transitions, and electrical conduction studies.

PC-Tue-P2 - Phase diagram of GaN — where is its wurtzite-rocksalt-liquid triple point?

2. Physics and characterization

Jacek Piechota[1]
Stanisław Krukowski[1], Bohdan Sadovyi[1], Petro Sadovyi[1], Sylwester Porowski[1], **Izabella Grzegory**[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142 Warsaw, Poland

Abstract text: Gallium nitride (GaN) technology has advanced significantly due to its excellent figures of merit for critical applications such as LEDs and high power–high frequency transistors. Nevertheless, several fundamental physical properties — including its phase diagram — of this pivotal semiconductor remain incompletely characterized. In this presentation, we combine experimental investigations with ab initio molecular dynamics (AIMD) simulations to elucidate the high-pressure, high-temperature (HP-HT) phase behavior of the Ga–N system over pressures up to 15 GPa [1].

Our AIMD simulations distinguish between the congruent melting of GaN into an atomic liquid and its decomposition, which results in the segregation of molecular nitrogen (N_2) and the formation of an atomic solution. By comparing these results with previous experimental and theoretical findings, we propose a coherent interpretation for a crucial segment of the GaN phase diagram.

Additionally, we present new simulation data on the melting of GaN in its high-pressure ($p > 50$ GPa) rocksalt phase. In particular, we determine the pressure–temperature (p–T) coordinates of the wurtzite–rocksalt–liquid triple point, an essential parameter for understanding phase transitions including congruent melting of GaN in its high pressure rocksalt phase. Finally, we outline an integrated experimental and theoretical roadmap aimed at completing the GaN phase diagram.

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PC-Tue-P3* - Subsurface Modification of the Valence Band in Wide Bandgap III-Nitrides Through Mn ions incorporation

2. Physics and characterization

Kamila Nowak[1]
Miłosz Grodzicki[2], Rafał Kuna[3], Detlef Hommel[4], Damian Pucicki[5], Edyta Piskorska-Hommel[4]
[1] Department of Nanometrology, Wrocław University of Science and Technology, Janiszewskiego 11/17, Wrocław, Poland, Łukasiewicz Research Network-PORT Polish Center for Technology Development, Stabłowicka 147, Wrocław, Poland
[2] Łukasiewicz Research Network-PORT Polish Center for Technology Development, Stabłowicka 147, Wrocław, Poland | Department of Semiconductor Materials Engineering, Wrocław University of Science and Tec
[3] Łukasiewicz Research Network-PORT Polish Center for Technology Development, Stabłowicka 147, Wrocław, Poland
[4] Łukasiewicz Research Network-PORT Polish Center for Technology Development, Stabłowicka 147, Wrocław, Poland | Institute of Low Temperature and Structure Research, Polish Academy of Sciences, Okólna
[5] Department of Nanometrology, Wrocław University of Science and Technology, Janiszewskiego 11/17, Wrocław, Poland | Łukasiewicz Research Network-PORT Polish Center for Technology Development, Stabłowic

Abstract text: III-nitride semiconductors, particularly gallium nitride (GaN) and aluminum gallium nitride (AlGaN), have significantly advanced semiconductor technology in electronics and optoelectronics. Alongside these developments, there has been growing interest in exploring new material classes, such as diluted magnetic semiconductors DMS, which with predicted high Curie temperature are expected to drive breakthroughs in the domain of spintronics. Beyond developing new material systems, optimizing surface interfaces remains crucial for maximizing device efficiency. Optimization of surface heterojunctions and metal contacts is essential for improving charge transport and overall performance. Thus, III-nitrides offer various surface modification possibilities, including phase segregation, passivation, and other material layer adsorption.

While several studies have explored surface modifications of III-nitrides using different deposited layers, valence band engineering in wide-bandgap materials such as AlGaN through diffusively implanted manganese remains largely unexplored, but still highly required. The prior research has been primarily focused on GaN. Although the growth conditions and material properties of GaN and AlGaN systems have been investigated over the years, the surface properties of Mn/AlGaN system remain largely unstudied. Moreover, it is still a great challenge to grow bulk AlGaMnN crystals using epitaxial growth methods, and even more so, there is no research on further surface modification of this class of materials. To address this gap, this study proposes modifying the subsurface properties of III-nitride materials (GaN, AlGaN) through transition metal deposition, diffusion and a new surface alloy formation.

Here, we present the effect of surface modification of GaN, AlGaN by manganese diffusion caused by thermal annealing, as well as the impact of manganese incorporation into the bulk AlGaN epitaxial layer. A thin manganese layer was deposited using plasma-assisted molecular beam epitaxy (PA-MBE) under ultra-high vacuum conditions. The surface properties of the resulting interfaces and the effects of annealing were examined using X-ray photoelectron spectroscopy (XPS). The

findings confirmed manganese diffusion into the semiconductor surface and the formation of Mn-based alloys with successful valence band modification.

PC-Tue-P4 - Process and Characterization of Ohmic Contacts to p-type GaN using Ni/NiO/ITO Multilayer Scheme

2. Physics and characterization

Taoufik Slimani Tlemcani[1]
Hicham Ait Lassri[1], Clément Berger[1], Micka Bah[1], Dimitri Bébien[1], Meriem Chettab[1], Matthew Charles[2], Romain Gwoziecki[2], Patrick Laffez[1], Daniel Alquier[1]
[1] GREMAN UMR 7347, Université de Tours, CNRS, INSA Centre Val de Loire, 37071 Tours, France
[2] Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA), University of Grenoble Alpes, Leti, 38000 Grenoble, France

Abstract text: The fabrication of low-resistance and thermally stable Ohmic contacts is essential for the obtention of reliable galium nitride (GaN) power devices. In the case of the *p*-type GaN, a thin Ni/Au bilayer is commonly used for Ohmic contacts. However, Au metal contacts are high cost, incompatible with the complementary metal-oxide-semiconductor (CMOS) foundries and exhibit poor thermal stability. Thus, seeking an alternative at affordable cost and thermally stable remains crucial. In the present study, we investigate Au-free Ohmic contact formation on *p*-type GaN using a multilayer Ni/NiO/indium tin oxide (ITO). First, Ni (2 nm)/NiO (50 nm) thin films were deposited by direct current (DC) magnetron sputtering. This bilayer acts as an intermediate layer doing a transition that facilitates hole injection by reducing the barrier height that may appear at the ITO/*p*-GaN interface. A 200 nm ITO thin films were then deposited via radio frequency (RF) magnetron sputtering at different temperatures (300°C, 400°C, and 500°C), followed or not by an additional annealing stage at 500°C in air ambient. We examined their structural, microstructural, and electrical properties using X-ray diffraction (XRD), scanning electron microscopy (SEM) as well as circular transfer length model (c-TLM) techniques, respectively. The ITO thin films deposited on *p*-GaN exhibited good crystallinity, along with a compact, dense, and granular structure with a homogeneous grain distribution. The films deposited at 400°C and annealed in air at 500°C demonstrated a low resistivity of 5×10^{-4} Ω.cm as determined by Hall effect measurements. Our results show that contact resistance can be significantly reduced using such multilayer after suitable annealing. We demonstrate that specific contact resistance for ITO/NiO/Ni on *p*-GaN can reach a value of 4.25×10^{-3} Ω.cm² for the sample with ITO deposited at 400°C and annealed at 500°C in air ambient. This work presents also methods for improving the electrical properties of the contacts to *p*-GaN and highlights the impact of deposition and annealing conditions on the formation of ohmic contacts using ITO on *p*-GaN, providing insights into optimizing the electrical performance for efficient GaN power diodes or transistors.

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PC-Tue-P5 - The Photoionization Processes of Deep Trap Levels in n-GaN Films grown by MOVPE on Ammono-GaN substrates

2. Physics and characterization

Piotr Kruszewski[1]
Konrad Sakowski[1], Krzysztof Goscinski[2], **Pawel Prystawko**[1]
[1] Institute of High Pressure Physics, PAS, Warsaw, Poland
[2] Institute of Physics, PAS, Warsaw, Poland

Abstract text: Deep trap levels in nitride-based materials like GaN or $Al_xGa_{1-x}N$ can be the source of parasitic conduction, free carriers compensation or recombination centers and can lead to premature device degradation. Therefore, the knowledge on the defect formation is a key factor for further progress in fabrication of high quality electronic and opto-electronic devices.
To study relatively shallow levels in GaN, the Deep Level Transient Spectroscopy (DLTS) [1] is commonly used, however the midgap states are thermally inactivated and do not contribute to measured signal. Therefore, to analyse the midgap states in wide bandgap materials, Deep Level Optical Spectroscopy (DLOS) [2] technique can be applied since in DLOS method, for incident photon energies equal to or higher than the optical ionization energy threshold (E_0), carriers are optically promoted to the bands.
In this paper, we present various theoretical models that accurately approximate the spectral density of the optical capture cross-section (σ_0) obtained through the analysis of the photo-capacitance transients using Deep Level Optical Spectroscopy (DLOS) measurements on semi-transparent Ni/Au Schottky diodes fabricated on n-GaN films. Theoretical models examined in this study involved a variety of approaches, from the Lucovsky model [3] that assumes no lattice relaxation to more sophisticated models like Chantre-Bois [2] and Pässler [4], which take into account the electron-phonon coupling phenomenona. By applying theoretical models to the experimentally determined data, we were able to estimate the photoionization and Franck-Condon energies. Finally, the results of our analysis confirm that the photoionization processes of deep traps in n-GaN grown by the metal organic vapor phase epitaxy technique (MOVPE) are strongly coupled to the lattice [5].

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PC-Tue-P6 - Annealed Mg Nanodot Arrays on GaN for P-Type Ohmic Contact with Improved Surface Morphology

2. Physics and characterization

Rong Teng[1]
Jia Wang[2], Wentao Cai[3], Yingying Lin[4], Haitao Wang[3], Hirotaka Watanabe[3], Xigen Li[5], Shun Lu[5], Yoshio Honda[6], Hiroshi Amano[6]
[1] School of Engineering, Nagoya University, Nagoya, Japan; School of Physics, Peking University, Beijing, China
[2] Institute for Advanced Research & Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan
[3] Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan
[4] Deep Tech Serial Innovation Center, Nagoya University, Nagoya, Japan
[5] Graduate School of Engineering, Nagoya University, Nagoya, Japan
[6] Institute of Materials and Systems for Sustainability & Institute for Advanced Research & Graduate School of Engineering, Nagoya University, Nagoya, Japan

Abstract text: Low-resistance ohmic contacts are crucial for GaN-based devices, especially for p-GaN, where achieving high hole concentration is challenging. Annealing metallic Mg on GaN has been proved effective in reducing the specific contact resistivity of p-GaN. However, the surface roughness associated with this method remains a limitation. A novel approach replaces continuous Mg films with Mg nanodot arrays (discontinuous hundred-nm-scale islands) for improved ohmic contact and smoother surfaces. Subsequent annealing enhances uniformity while controlling GaN-Mg reactions during Mg intercalation into the GaN lattice.

In this study, we investigate the influence of annealed Mg nanodot arrays on the ohmic contact resistance and surface morphology of lightly doped p-GaN ([Mg] = 7×10^{18}cm^{-3}). Square arrays of nanodot patterns with varying hundred-nm-scale diameter and filling ratios from 0% (bare GaN) to 100% (continuous Mg film) were prepared via e-beam lithography and e-beam evaporation process. Samples then underwent rapid thermal annealing (800°C, N_2, 15 min) and acid cleaning.

Post-annealing surface characterization was performed using optical microscopy (OM), scanning electron microscopy (SEM) and atomic force microscopy (AFM). OM observations revealed increased transparency with lower filling ratios, while SEM images further indicated reduced surface roughness compared to the 100% filling ratio sample. AFM measurements confirmed this trend, suggesting that the annealing of Mg nanodots results in smoother surface morphology. Meanwhile, HAADF-STEM images verified the formation of Mg-intercalated GaN superlattices beneath the nanodot-annealed areas, aligning with previous findings for continuous Mg films.

Ni/Au contacts were deposited and sintered for TLM and Hall tests. TLM showed low contact resistance R_c maintained down to 40% filling ratio (further reductions in the filling ratio led to a sharp increase due to the limited Mg-annealed area), demonstrating that a good ohmic contact, comparable to that achieved with continuous Mg film, can be realized by Mg nanodots. Furthermore, smaller filling ratio unexpectedly led to a reduction in sheet resistance R_{sh} and an increase in sheet carrier concentration. This trend persisted until filling ratio<20%, implying significant in-plane Mg diffusion, which will be further investigated in future studies.

PC-Tue-P7 - Deep-Level Transient Spectroscopy evaluation of epilayers grown on bulk GaN substrates for vertical devices

2. Physics and characterization

Pedro F. P. P. Rocha[1]
Kevin Nadaud[1], Giuseppe Greco[2], Taoufik Slimani Tlemcani[1], Michal Bockowski[3], Florian Bartoli[4], Eric Frayssinet[4], Yvon Cordier[4], Fabrizio Roccaforte[2], Daniel Alquier[1]
[1] GREMAN UMR 7347, Université de Tours, CNRS, INSA Centre Val de Loire, 37071 Tours, France
[2] Consiglio Nazionale delle Ricerche – Istituto per la Microelettronica e Microsistemi (CNR-IMM), Catania, Italy
[3] Institute of High-Pressure Physics – Polish Academy of Science (IHPP-PAS), Warsaw, Poland
[4] Université Cote d'Azur, CNRS, CRHEA, Valbonne, France

Abstract text: GaN-based lateral power devices such as High Electron Mobility Transistors are now under industrial development. However, vertical device structures are necessary to achieve higher breakdown capabilities and increase the compactness of GaN-based power devices. To ensure the quality of available substrates lattice matched with GaN, it is crucial to characterize epilayers in detail especially focusing on deep carrier traps. These traps can indeed compensate the drift layer doping, affect the leakage current, the switching losses and the breakdown voltage, impacting the global device performance. Deep-Level Transient Spectroscopy (DLTS) is a commonly used technique to characterize deep carrier traps. While numerous reports have identified different traps in GaN-on-GaN epilayers, few studies compare the quality of epilayers grown on different GaN substrates. Therefore, in this work, four different epilayers grown on different available substrates were characterized through DLTS analysis on identical Schottky diodes.
The DLTS measurements were performed on 300 µm diameter contacts with two bench configurations; one for multiple measurements and another to reach 80 K. The analysis using the Fourier Transform b_1 coefficient reveals three electron traps. The energy levels are around 0.09-0.15 eV for trap E1, 0.48-0.56 eV for trap E2, and 0.78-0.91 eV for trap E3. The first two traps are commonly observed in GaN-on-GaN epilayers as V_N and Fe_{Ga} point defects respectively. The third trap is not systematically observed and is often attributed to dislocations. By increasing the filling time pulse between 2×10^{-5} to 0.6 s, the E3 trap maximum follows logarithmically the time pulse width with a saturation around 0.1 s. This behaviour confirms the extended defect nature (dislocation-related) of E3 trap.
The comparison between the Schottky diode devices reveals that the epilayer grown on the ammonothermal substrate showcases an E2 trap concentration lower by one to two orders of magnitude and the absence of E3 traps. The latter can be explained by the lower dislocation density (in the order of 10^4 cm^{-2} vs 10^6-10^7 cm^{-2} for other substrates) observed by cathodoluminescence on ammonothermal substrates. Therefore, this comparison highlights the higher quality of ammonothermal substrates.

PC-Tue-P8 - Role of deep traps in thermal stability of resistivity in bulk ammonothermal GaN:Mg

2. Physics and characterization

Marcin Zajac[1]
Leszek Konczewicz[2], Karol Pozyczka[2], Kacper Sierakowski[2], Karolina Grabianska[2], Robert Kucharski[2], Roman Kozlowski[3], Pawel Kaminski[3]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw,
[3] Lukasiewicz Research Network – Institute of Microelectronics and Photonics, Warsaw, Poland

Abstract text: In ammonothermal (Am) method Mg can be used to obtain p-type and semi-insulating (SI) GaN substrates by appropriate compensation of unintentional oxygen donors. Precise knowledge on native point defects properties is essential for shaping the crystal electrical properties. Recently, both Ga vacancies (V_{Ga}) related complexes and nitrogen displacement defects, like N vacancies (V_N) and N interstitials (N_i) were detected [1]. In this communication we will identify other traps and discuss microscopic mechanisms responsible for compensation and resistivity changes by annealing at temperatures higher than the Am growth temperature (500 °C) for different Mg content.

GaN:Mg crystals with Mg concentrations 5×10^{18} cm^{-3} - 1×10^{20} cm^{-3} and a fixed oxygen content (1×10^{18} and 1×10^{19} cm^{-3}) were studied by Hall effect measurements vs temperature in the range 300°C-800°C and by Laplace Photo-induced Transient Spectroscopy (LPITS).

It is shown that as-grown samples have p-type conductivity. The activation energy of conductivity s, determined from the slope of the s vs. temperature, can be tuned from 1.6 eV, through 1.3 eV - 0.8-eV, 0.5 eV to 0.15 eV with increasing the Mg concentration, indicating Fermi level pinning to different deep traps: $V_N^{3+/+}$, $N_i^{3+/2+}$, $N_i^{2+/+}$[1] (0.5eV), V_{Ga} – related complexes of closely spaced +/0 transition levels (0.8-1.2 eV) and also $V_{Ga}^{0/-}$, $V_{Ga}^{-/2-}$ (1.5-1.6 eV). At the same time LPITS confirmed these results, showing the presence of a number of traps with activation energies in the range of 0.2–1.6 eV. Beside aforementioned defects, the additionals ones should be taken into consideration, identified as Ga interstitials (Ga_i) and Ga antisites (Ga_N) - the latter one with activation energy of 1.3 eV, corresponding to a hole trapping to $Ga_N^{3+/2+}$ donor level. This suggests formation of the Ga_N by recombination of mobile Ga_i with V_N. This process is enhanced by high temperature annealing, leading to raise of the Fermi level, monitored experimentally by increased resistivity. The solution of the charge neutrality equation allowed to describe the change of compensation mechanism quantitatively. The presented results indicate a crucial role of deep defects in optimizing the properties of SI Am-GaN:Mg by finding a proper Mg concentration to maintain a sufficiently high resistivity during device epitaxy.

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PC-Tue-P9 - Effects of Tilt Angle and Dose on Mg Channeled Implantation into GaN(0001)

2. Physics and characterization

Atsushi Suyama[1]
Hideaki Minagawa[2], Masahiko Aoki[2], Kazuhiro Yokota[2], Hitoshi Kawanowa[2], Jun Suda[1]
[1] Nagoya University, Nagoya, Japan
[2] Ion Technology Center Co., LTD, Hirakata, Japan

Abstract text: Channeled implantation of magnesium (Mg) ions [1], which enables deep implantation with minimal damage, has attracted significant attention as a fabrication process for vertical GaN power devices [2]. However, there have been few experimental studies on Mg channeled implantation, particularly regarding the effects of misalignment in the incident angle and accumulated lattice disorder on Mg depth profiles. In this study, we experimentally evaluated the effects of implantation tilt angle and Mg dose on Mg depth profiles using secondary ion mass spectrometry (SIMS). Additionally, we performed computer simulations using MARLOWE [3], a Monte Carlo simulation designed to model channeling phenomena. Based on experimental results, we proposed an empirical simple model to reproduce the Mg depth profiles.

We performed channeled implantation of Mg into GaN (0001) free-standing substrates. The tilt angle, defined as the deviation from the perpendicular direction to the (0001) crystal plane, was varied from 0° to 7° at a Mg dose of 1×10^{14} cm^{-2} with an implantation energy of 180 keV. It should be noted that the (0001) crystal plane was precisely determined by X-ray diffraction for each sample. To investigate Mg dose dependence, channeled implantations were performed at a tilt angle of 0° and an implantation energy of 180 keV with various Mg doses ranging from 5×10^{12} cm^{-2} to 5×10^{14} cm^{-2}.

A tilt angle below 0.5° had no significant effect on channeling. However, when the tilt angle reached 1°, a notable change in the Mg depth profile was observed. Regarding Mg dose dependence, no significant effect was observed for doses below 5×10^{12} cm^{-2}. As the Mg dose increased, the Mg depth profiles exhibited a growing random implantation component due to dechanneling, caused by accumulated lattice disorder during implantation. We developed a method to reproduce these results using MARLOWE. Details of the implantation damage modeling, simulation approach, and the dependence of Mg depth profiles on Mg dose and tilt angle will be discussed in the presentation.

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PC-Tue-P10 - Properties of defects formed during GaN growth as a result of hillock coalescence

2. Physics and characterization

Tomasz Sochacki[1]
Magdalena Zajac[1], Robert Kucharski[1], Karolina Grabianska[1], Matthieu Paillet[2], Sandrine Juillaguet[2], Leszek Konczewicz[1], **Marcin Zajac**[1], Jan Weyher[1], Patrik Stranak[3], Lutz Kirste[3], Sylvie Contreras[2], Michal Bockowski[1]
[1] Institute of High Pressure Physics Polish Academy of Sciences, Warsaw, Poland
[2] Laboratoire Charles Coulomb (L2C), University of Montpellier, CNRS, Montpellier, France
[3] Fraunhofer Institute for Applied Solid State Physics (IAF), Freiburg, Germany

Abstract text: Gallium nitride (GaN) is essential for optoelectronic and electronic devices. Bulk GaN is produced via three main techniques: Halide Vapor Phase Epitaxy, ammonothermal, and sodium flux methods. These techniques are being developed to improve crystal quality and uniformity [1]. Advancing these technologies requires fundamental studies of growth mechanisms. Thus, analyzing bulk crystal morphology at each growth stage is crucial. Ensuring stability during crystallization, regardless of the method, is important for achieving a crystal with uniform composition and structural quality. The most consistent growth pattern involves growth on a single hillock. This stage is usually preceded by a phase in which hillocks merge, which can lead to disturbances in growth morphology [2]. Disruptions at the crystallization front, such as transitions from step propagation to step bunching or meandering on hillock slopes, significantly impact crystal quality. These disruptions can lead to inclusions, point defects, altered impurity incorporation, and dislocation generation [3].

This study introduces a universal model for GaN growth on a misoriented native seed, examining the growth stages and their impact on the crystal's properties and structural quality. The evolution of crystal growth will be illustrated, from step propagation through the reformation of the (0001) or (000-1) plane, depending on the growth method, to hillock formation. Furthermore, the influence of different growth modes on the structural quality of the resulting layers will be analyzed in detail. Additionally, this work explores the properties of regions with disturbed morphology that emerge at the junction of two merging growth hillocks. The study presents results from photo-etching, X-ray topography, Raman effect measurements and electrical transport measurements conducted over a temperature range of 9K to 700K. All the above-mentioned experimental techniques confirm the fact that the regions at the junction of two contacting hillocks are characterized by a lower free carriers concentration compared to the rest of the crystal. Impurity content analysis performed using Time-of-Flight Secondary-ion Mass Spectrometry will be discussed

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PC-Tue-P11 - From GaN to Contact Electrification Induced Interface Spectroscopy

2. Physics and characterization

Ding Li[1]
Weiguo Hu[1], Junyi Zhai[1], Zhong Lin Wang[1]
[1] University of Chinese Academy of Sciences, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, 101408, China.

Abstract text: This report will focus on multiphase interatomic electron transfer and use GaN materials as carriers to introduce their developments in Piezo-optoelectronics, Tribovoltaic Effect, and Contact Electrification Induced Interface Spectroscopy (CEIIS), covering from basic principles to typical field applications. Firstly, I will introduce the Piezo-optoelectronics Effects based on GaN and their applications. Next, I will introduce the Tribovoltaic Effect and its applications. Finally, I will focus on an emerging field – CEIIS. We observed the atomic featured photon emission spectra during CE between two solid materials for the first time. The photon emissions are the evidences that electrons transfer takes place at the interface from one atom in one material to another atom in the other material during CE. It conveys a wealth of information about the energy structure at the interface and naturally paves a way to a spectroscopy corresponding to the contact-electrification at an interface, which might have fundamental impacts to understand the interaction among solids, liquids and gases. Although we only focused on photon emission in CE for solid-solid case in this study, it could be expanded to Auger electron excitation, X-ray emission and electron emission in CE for general cases, which remain to be explored.

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PC-Tue-P12* - Red Emission of GaN:Eu Films Grown by Plasma-Assisted Molecular Beam Epitaxy: Effects of Europium Concentration and Magnesium Co-Doping

2. Physics and characterization

José Cardoso[1]
Alvaro Revilla-Martin[2], Bruno Daudin[2], Katharina Lorenz[3], Luis Rino[1], Teresa Monteiro[1], Maria do Rosário Correia[1]
[1] i3N & Physics Department, Universidade de Aveiro, Aveiro, Portugal
[2] IRIG PHELIQS/NPSC, CEA-Grenoble, Grenoble, France
[3] INESC-MN & IPFN, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

Abstract text: One of the biggest unsolved challenges in III-N technology is to obtain efficient red light-emitting diodes (LEDs). This obstacle has limited the implementation of monolithic full-color displays and has become even more urgent with the growing interest in III-N-based micro-LED technology. In this sense, the adoption of Eu-doped GaN LED structures has been proposed as an alternative to overcome the low efficiency of conventional InGaN-based red emitters, having already achieved efficiencies up to ~10% in multi-layered GaN/GaN:Eu LEDs doped during growth by organometallic vapor phase epitaxy [1]. Better color purity and stability against current density and temperature are also advantages of this approach. However, efficiencies of ~10% are still low and must be improved to be at the level of InGaN-based blue and green LEDs (~80% and 50%, respectively). To this end, it is crucial to control the GaN:Eu growth to promote the incorporation of Eu into sites with high luminescence efficiency and excitation cross-section.

Depending on the growth method and respective growth parameters, different Eu centers can be favored, impacting the performance of LEDs. This work studies the incorporation and optical activation of in situ doped Eu in GaN grown by plasma-assisted molecular beam epitaxy. Two growth parameters are controlled: i) the Eu cell temperature, leading to Eu concentration between 0.1% and 0.4% (measured by RBS), and ii) the Mg cell temperature from 210 ℃ to 280 ℃ (expected concentrations from ~1×10^{19} cm^{-3} to 5×10^{19} cm^{-3}, respectively). The effects of such parameters on the optical properties of the samples are evaluated using optical spectroscopy techniques, such as steady-state and time-resolved photoluminescence (PL and TRPL), PL excitation (PLE), and micro-Raman spectroscopy. Selective excitation and TRPL allow the identification of multiple Eu centers, whose relative contribution depends on the growth parameters. Interestingly, for high Mg cell temperatures, besides the observation of local vibrational modes related to Mg and Mg-H complexes, the Eu-related PL signal decreases abruptly, and new Eu centers are formed. According to RBS, Eu concentration does not change upon Mg incorporation.

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PC-Tue-P13 - Unveiling N-Polar III-Nitride MOCVD Growth on SiC: Atomic-Scale Insights and Optimization via ADF STEM

2. Physics and characterization

Ingemar Persson[1]
Hengfang Zhang[2], Alexis Papamichail[2], Plamen Paskov[2], Vanya Darakchieva[3]
[1] Centre for Analysis and Syntehsis (CAS), Lund University
[2] Competence Center for III-Nitride Technology, C3NiT-Janzén, Department of Physics, Chemistry and Biology (IFM), Linköping University
[3] Solid State Physics and NanoLund, Lund University

Abstract text: GaN and AlN-based semiconductors have gained considerable interest for advanced optoelectronic, and electronic device applications, because the spontaneous and piezoelectric polarization in the *c*-direction to tune transport properties at interfaces. It is established that GaN/AlN(000), denoted nitrogen-polar (N-polar), heterostructures offer an advantage in high electron mobility transistors (HEMTs) by means improved confinement of the two-dimensional electron gas (2DEG) as well as reduced on-resistance.[1] Notably, high quality N-polar nitrides require foreign offcut substrates where the step-flow growth mode that follows leads to anisotropic mobilities along and across terraces and steps, limiting device design options. [2-4] We have recently shown the sequential temperature growth steps of N-polar GaN on *m*-plane offcut 4H-SiC has been shown to further improve crystallinity, and reduce surface roughness, dislocation density, and incorporation of unintentional impurities. [5]

Here we report on N-polar GaN/AlN interfaces grown by hot-wall MOCVD on 4H-SiC (000) with 1° and 4° m-plane offcuts. A new type of vertical inversion domain boundary (IDB) is identified on step-flow grown GaN on 4° m-plane offcut 4H-SiC. In contrast, an offcut angle of 1° shows no vertical IDBs but on the other hand results in hexagonal hillocks and nm-sized surface pits. We further show that the GaN surface on the 4° offcut consists of two terraces with opposing polarity as a direct result of vertical IDBs originating from the 4H-SiC surface. The N-polar to M-polar surface area ratio is directly proportional to the step density at the 4H-SiC surface, which in turn is related to the substrate offcut angle. That is for an offcut of 4° toward the m-plane 14% of the surface is M-polar. This discovery may be key to future understanding of N-polar device performance and stress the need for rigorous polarity determination techniques that can resolve nm-sized mix-polar terraces.

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PC-Tue-P14* - Studies on Threshold Voltage Instabilities in Vertical Trench GaN MOSFETs with Different Gate Oxides

2. Physics and characterization

Veronica Zhan Gao[1]
Maciej Kamiński[2], Aneta Gołębiowska[2], Aleksander Szczepański[1], Krzysztof Urbanowski[1], Jarosław Tarenko[2], Oskar Sadowski[2], Justyna Wierzbicka[1], Aleksandra Wójcicka[1], Wojciech Hendzelek[1], Kamil Kosiel[1], Anna Szerling[1], Paweł Prystawko[3], Michał Boćkowski[3], Izabella Grzegory[3], Andrzej Taube[1]
[1] Sieć Badawcza Łukasiewicz Instytut Mikroelektroniki i Fotoniki, aleja Lotników 32/46, 02-668 Warszawa, Poland
[2] Sieć Badawcza Łukasiewicz Instytut Mikroelektroniki i Fotoniki, aleja Lotników 32/46, 02-668 Warszawa, Poland; Warsaw University of Technology, Pl. Politechniki 1, 00-661 Warsaw, Poland
[3] Institute of High Pressure Physics Polish Academy of Sciences, ul. Sokolowska 29/37, 01-142 Warsaw, Poland

Abstract text: Vertical trench MOSFETs offer high breakdown voltage scaling independent of chip size, enhancing efficiency while reducing cost [1]. This study investigates the effects of Al_2O_3, SiO_2, and Al_2O_3/SiO_2 bilayer gate oxides on threshold voltage (V_{TH}) instability in vertical trench GaN MOSFETs.

Two device groups were fabricated: Group A with monolayer gate oxides (50 nm Al_2O_3 using H_2O (A1) or O_3 (A2), and 50 nm SiO_2 (A3)), and Group B with a bilayer oxide (20 nm Al_2O_3 + 50 nm SiO_2). Forward (FW) (10 V to $V_{GS,max}$) and backward (BW) sweeps ($V_{GS,max}$ to 10 V) were performed, incrementally stepping $V_{GS,max}$ from 0 to -10 V.

In A1 and A2 (both 50 nm Al_2O_3), overlapping FW sweep I_DV_{GS} curves indicated minimal trapping accumulation. But BW sweeps exhibited increasing negative V_{TH} shifts, from -0.04 V (A1) and -0.95 V (A2) at $V_{GS,max}$ = -3 V to -1.09 V (A1) and -2.54 V (A2) at $V_{GS,max}$ = -10 V. The SS also increased, indicating charge buildup due to negative $V_{GS,max}$ stress. A2 (O_3-based Al_2O_3) showed higher interface trap density than A1, highlighting the oxygen source's impact on trap formation.

A3 (50 nm SiO_2) showed V_{TH} shifts in both FW and BW sweeps, suggesting trapping under positive gate bias and/or memory effects. When $V_{GS,max}$ exceeded -3 V, positive shifts (up to 4.5 V) and a 70% I_D decrease indicated trench sidewall trapping. In Group B (bilayer oxide), a similar pattern appeared: an initial negative V_{TH} shift at small $V_{GS,max}$, and positive shifts at higher $V_{GS,max}$, with SS increasing significantly. Due to memory effects from hole traps in the bilayer stack.

In general, detrapping of pre-existing traps in Al_2O_3 or at the Al_2O_3/GaN interface cause negative V_{TH} sfhit at the trench bottom under negative bias, while hole injection through SiO_2 to the p-GaN sidewalls reduces I_D under positive bias. The Al_2O_3/SiO_2 bilayer design partially mitigates these two effects, reducing current loss. However, memory effects of hole traps and the energy gap between the SiO_2 and Al_2O_3 lead to SS increase, which requires optimization to further improve device switching speed.

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chain for vertical GaN-on-GaN power electronics: from GaN substrate to Intelligent Energy Bank".

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PC-Tue-P15* - Impact of Charge Trapping on Threshold Voltage Instability in Quasi-Vertical GaN Trench MOSFETs on Sapphire

2. Physics and characterization

Haowen Luo[1]
Renqiang Zhu[2], Xuancong Fan[1], Kei May Lau[2], **Huaxing Jiang**[1]
[1] School of Integrated Circuits, South China University of Technology, Guangzhou, China
[2] Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China

Abstract text: Vertical GaN trench MOSFETs have demonstrated enormous potential for power electronics [1]. However, the device threshold voltage (V_{th}) instability remains a severe issue yet to be well understood. This work investigates the impact of charge trapping effects on the V_{th} instability in quasi-vertical GaN trench MOSFETs on sapphire under bipolar pulsed gate operation. The V_{th} and hysteresis ($\triangle V_{th}$) of the device show strong dependence on the gate pulse width and quiescent gate bias (V_{GSQ}).

Fig. 1 shows the device cross-sectional schematic. The fabrication process can be found in our previous work [2,3]. The device shows a V_{th} of 4.7 V with a large hysteresis of 1 V under double-sweep DC transfer measurement (Fig. 2). In contrast, a V_{th} of 1.26 V with minimal $\triangle V_{th}$ is observed under gate pulsed operation with a V_{GSQ} of -10 V and pulse width/period of 2 ms/500 ms. Moreover, when the V_{GS} is double swept between 0 V and 15 V in gate pulsed mode, the V_{th} decreases with the decrease of negatively biased V_{GSQ} (Fig. 3) while increases with the gate pulse width (Fig. 4). The $\triangle V_{th}$ remains almost a constant of 0.3 V for the V_{GSQ} decreasing from 0 V to -6 V, whereas the $\triangle V_{th}$ turns to be -0.2 V when the V_{GSQ} further decreases to -10 V. The $\triangle V_{th}$ is around 0.25 V for the gate pulse width varying from 2 ms to 400 ms with a V_{GSQ} of -5 V. In addition, the V_{th} decreases monotonically while the $\triangle V_{th}$ shows a first increase and then decrease trend, when the temperature increases from 25°C to 150°C (Fig. 5). Fig. 6 shows the energy band diagrams of the gate stack. Under positive gate bias, part of the electrons in the inverted channel are trapped in the gate stack, leading to a positive shift of V_{th}, as evidenced by the increased V_{th} with the increase of gate pulse width; during the negative quiescent gate bias stage, trapped electrons are de-trapped and holes may also be captured, leading to a greatly reduced V_{th} and $\triangle V_{th}$ compared to DC results. The negative shift of V_{th} with increased temperature is mainly due to the increase of intrinsic carrier concentration while the charge trapping in the gate stack is suppressed with proper pulse setting.

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PC-Tue-P16* - GaN FinFETs and High-k Dielectrics: A Synchrotron XPS Study of Interface Chemistry

2. Physics and characterization

Shreemoyee Chakraborty[1]
Adamantia Logotheti[2], Nishant Patel[1], Ata Jafarzadeh[1], Byeongchan So[1], Jovana Malm[1], Erik Lind[3], Vanya Darakchieva[1], Rainer Timm[1]
[1] Dept. of Physics and NanoLund, Lund University, 221 00 Lund, Sweden
[2] Dept. of Physics and NanoLund, Lund University, 221 00 Lund, Sweden; Volvo Car Corporation, 405 31, Gothenburg, Sweden
[3] Dept. of Electrical and Information Technology, Lund University, 221 00 Lund, Sweden; Volvo Car Corporation, 405 31, Gothenburg, Sweden

Abstract text: Gallium nitride (GaN), a wide band gap semiconductor, is a crucial material for next-generation power electronics, enabling energy-efficient switching at high frequencies. To achieve further miniaturization together with better electrical performance, improved gate oxides with a high dielectric constant (high-k oxides) are needed. Lateral power device structures face challenges such as heat dissipation and large chip area requirements. As a result, vertical MOS field-effect transistors (MOSFETs) with a fin-shaped structure (FinFETs) are a promising route for GaN-based power devices. Atomic layer deposition (ALD) is the preferred method for producing uniform, ultrathin oxide films such as HfO_2 or Al_2O_3 on GaN. However, understanding of the GaN/high-k oxide interface quality, which is crucial for the device performance, remains limited. ALD processes vary significantly depending on the cleaning procedure, particularly in the case of nitrides; hence a systematic investigation of the influence of pre-ALD treatment is needed.

In this study, we investigated the GaN/high-k oxide interface using synchrotron-based X-ray photoelectron spectroscopy (XPS) through two approaches. First, we examined the effects of different high-k oxide materials (HfO_2 and Al_2O_3) and pre-ALD treatments (e.g., HCl/HF etching) on planar nitride samples. Oxide films were deposited using 20 ALD cycles, yielding approximately 2µm-thick films. High-resolution spectra of Ga 3d, N 1s, O 1s, Hf 4f, Al 2p, and C 1s core levels, along with valence band spectra, were analysed. The Al_2O_3 films were found to be thinner than the HfO_2 films, despite of the same number of ALD cycles, and of more homogeneous stoichiometry, aligning the fin structures in the ca. 30 µm wide X-ray beam such that most of the XPS signal originated from the vertical fin surfaces (GaN a-facets). Fin structures with both HfO_2 or Al_2O_3 show significant binding energy shifts compared to planar samples, with different behavior between Ga 3d and O 1s core-levels, suggesting variations in Fermi level position and interface chemistry. These insights are crucial for optimizing high-k ALD on GaN, ultimately improving power electronic devices with significant industrial and societal impact.

PC-Tue-P17* - Defects in Ammonothermal-based GaN Vertical Power Devices

2. Physics and characterization

Andrew Winchester[1]
Dara Weiss[2], Michael Mastro[3], Travis Anderson[4], Jennifer Hite[5], Behrang Hamadani[2], Sujitra Pookpanratana[1]
[1] Nanoscale Device Characterization Division, National Institute of Standards and Technology, Gaithersburg, MD, USA
[2] Building Energy and Environment Division, National Institute of Standards and Technology, Gaithersburg, MD, USA
[3] U.S. Naval Research Laboratory, Washington, DC, United States
[4] U.S. Naval Research Laboratory, Washington, DC, United States; Department of Chemical Engineering, University of Florida, Gainesville, FL, USA
[5] U.S. Naval Research Laboratory, Washington, DC, United States; Department of Materials Science and Engineering, University of Florida, Gainesville, FL, USA

Abstract text: Next generation gallium nitride (GaN) power devices aim to achieve higher operation voltages by moving from lateral to vertical architectures using epitaxial growth on bulk GaN substrates. However, the limited quality and size of bulk substrates along with their high cost has hindered development. Newer bulk GaN growth schemes, such as the ammonothermal method, can produce large substrates with low densities of structural defects such as dislocations, which are often associated with reverse bias leakage current in more traditional hydride vapor phase epitaxy (HVPE) grown substrates. However, the effect of defects in ammonothermal GaN substrates on device operation is still under intense study, and it is possible that both extended and point defects arising due to the different growth conditions will cause different device issues than in HVPE-based substrates.

Here, we investigate extended and point defects in epitaxial GaN grown via MOCVD on ammonothermal and HVPE GaN substrates. In p-i-n diodes we find that devices on ammonothermal substrates often fail reverse bias breakdown tests and suffer from higher leakage current compared to diodes on HVPE substrates. Electroluminescence spectroscopy reveals differences in the radiative emission in the diodes, implying that the ammonothermal devices have a different distribution of impurity defects. The wide variation in device performance suggests extended defects are also likely important, which we examined on epitaxial films from the same growths. We observe elongated triangular defects that occur on particular growth ridges of GaN films on ammonothermal substrates. These defects show altered electronic structure, are more resistive than the surrounding GaN, and appear to continue sub-surface, suggesting they may nucleate deeper in the epitaxy and be related to stacking faults. On epitaxy grown on HVPE substrate, we instead find defects due to pits with extending cracks near the patterned strain centers on the substrate, suggesting that they are related to dislocation bundles. Our results demonstrate that while the overall structural quality of ammonothermal substrates may be high, there are still factors related to defect nucleation, propagation, and composition that must be better controlled to achieve reliable high performance power electronic devices.

PC-Tue-P18* - Quantitative Investigation of Ultra-Low Thermal Boundary Resistance Mechanisms at Diamond/GaN Heterojunctions

2. Physics and characterization

Haolun Sun[1]
Mei Wu[1], Yuanmeng Xiang[1], Ling Yang[1], Xiaohua Ma[1], Yue Hao[1]
[1] National Engineering Research Center of Wide Band-gap Semiconductor, Xidian University, Xian, China

Abstract text: GaN-based high-electron-mobility transistors (HEMTs) have experienced rapid development in high-power and high-frequency applications. However, self-heating effects have resulted in significant thermal management challenges. The integration of diamond films on the top surface of these devices has been proposed as an effective approach to mitigate self-heating, attributed to the exceptionally high thermal conductivity (TC) of diamond. During this integration process, the thermal boundary resistance (TBR) at the diamond/GaN interface has been identified as a critical factor affecting the overall thermal performance of the devices.

With the application of dielectric layers, one of the most significant challenges in integrating polycrystalline diamond on GaN devices is achieving low thermal boundary resistance (TBR). Previous studies have demonstrated that SiNx layers have grown by MOCVD can effectively reduce TBR. This reduction is attributed to enhanced carbon diffusion into SiNx during diamond growth, which is controlled by plasma power and chamber pressure.

In this study, a combined model of DMM (Diffuse Mismatch Model) and MD (Molecular Dynamics) simulation was employed to reduce the computational complexity of first-principles calculations. The thicknesses of different material layers were determined using TEM (Transmission Electron Microscopy) and EDS (Energy Dispersive Spectroscopy). MD simulations were performed to determine the thermal resistance of mixed layers at different carbon diffusion levels and the phonon velocities required for the DMM model. The total TBR calculation formula is shown in Equation 1. The theoretical TBR was calculated at various carbon diffusion levels. Results showed that at a thermal resistance of 3.0 m^2K/GW, the sample exhibited 33.7% carbon diffusion, with mixed layer resistance accounting for 56.27% of the total.

$$TBR_{eff,Dia/AlGaN} = L_{eff}/K_{eff} = TBR_{Dia/mixed\ layer} + R_{mixed\ layer} + TBR_{mixed\ layer/AlGaN}$$

A theoretical model correlating thermal resistance with layer thickness at different carbon diffusion concentrations was established using combined DMM and MD simulations. The model predictions showed less than 10% deviation from experimental results.

PC-Tue-P19 - Correlation Study of AlGaN/GaN HEMT Structures Performed with Novel Wafer Level Capacitance Mapping Technique and Spectroscopic Ellipsometry

2. Physics and characterization

Marshall Wilson[1]
Dmitriy Marinskiy[1], Adam Wincukiewicz[1], Carlos Almeida[1], Ivan Shekerov[1], Jacek Lagowski[1], Anna Bölcskei-Molnár[2], Peter Basa[2], Fanni Flach[2], Zsolt Szekrényes[2], Leon Schiller[3], Sven Besendoerfer[3]
[1] Semilab SDI, Tampa,FL USA
[2] Semilab, Budapest, Hungary
[3] Fraunhofer IISB, Erlangen, Germany

Abstract text: In general, a correlation study is the statistical comparison of a range of different properties and the investigation of relations amongst them. For the purpose of epitaxial process tuning, it is essential to perform such correlations in a fast and reliable way on a full wafer-scale. In this work this is demonstrated by mapping of 200mm AlGaN/GaN HEMT wafers and analyzing different material and electrical properties corresponding to the same sites. Measurements were performed with a Corona noncontact Capacitance-Voltage metrology tool (CnCV). This technique includes biasing with corona charge deposition, ΔQ, and noncontact measurement of the surface voltage response, V, with a Kelvin probe. For fast wafer mapping, a novel CnCV "kinetic mode" approach was used wherein short millisecond duration UV pulses follow a single large negative corona charge, removing the charge in steps for the C-V measurement [1]. The HEMT structure active layer parameters determined from C-V characteristics include the pinch-off voltage, V_P, the two-dimensional electron gas sheet density, N_S, and the electrical thickness of the $Al_xGa_{1-x}N$ barrier layer, d_{AlGaN}. The aluminum composition x, and the optical AlGaN thickness were additionally measured by spectroscopic ellipsometry and photoluminescence on the same wafer sites.

The results show radial symmetry distribution patterns visible in V_P, N_S, d_{AlGaN}, optical AlGaN thickness, and x with the following findings:

1. Uniformity of d_{AlGaN}, optical AlGaN thickness, and x does not guarantee uniformity of N_S and V_P. This is demonstrated by results on a wafer with 1σ=1.1% and 2.0% for d_{AlGaN} and x, respectively, while exhibiting 1σ = 20% and 34% for N_S and V_P, respectively.
2. An anticorrelation between N_S and d_{AlGaN} was observed on some wafers, opposite to general literature expectations [2], and could be explained by an opposite spatial variation in x which dominates N_S compared to that of d_{AlGaN}.

The results show the importance of a complete multiparameter characterization of 2DEG wafer uniformity and a need for inclusion of other elements in modeling in addition to the AlGaN thickness and Al composition.

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PC-Tue-P20* - Gate-Controlled Rashba and Dresselhaus Spin-Orbit Coupling in AlGaN/GaN heterostructures

2. Physics and characterization

Shuaiyu Chen[1]
Ning Tang[1], Zhenhao Sun[1], Haoran Fan[2], Fuqiang Guo[1], Yifan Wang[1], Shixiong Zhang[3], Xuelin Yang[1], Xi Lin[2], Weikun Ge[1], Bo Shen[1]
[1] State Key Laboratory of Artificial Microstructure and Mesoscopic Physics and Frontiers Science Center for Nano-optoelectronics, School of Physics, Peking University, Beijing 100871, China.
[2] International Center for Quantum Materials, Peking University, Beijing 100871, China.
[3] College of Physics and Electronic Science, Hubei Normal University, Huangshi 435002, China.

Abstract text: Gate-controlled modulation of spin-orbit coupling (SOC) is pivotal for semiconductor spintronic device development. Here, an anomalous reduction in the total SOC coefficient of the two-dimensional electron gas in AlGaN/GaN heterostructures is observed, despite an increase in the Rashba term with gate voltage, as revealed by beating patterns in Shubnikov-de Haas oscillations. While the Rashba contribution rises with the gate-induced electric field, the Dresselhaus term is significantly enhanced by stronger quantum confinement in the triangular quantum well. The comparable magnitudes and opposite signs of Rashba and Dresselhaus SOC result in a net decrease in the total SOC coefficient. This tunable Dresselhaus SOC via gating enables electrical control of spin precession in spin transistors. Precise balancing of Rashba and Dresselhaus contributions provides a pathway to prolonging spin relaxation times and realizing persistent spin helix states in semiconductor heterostructures.

PC-Tue-P21* - Thermal transportation analysis of GaN channel layer in N-polar GaN HEMT using neural network potential

2. Physics and characterization

Shigeki Yoshida[1]
Takuji Yamamura[1], Juniji Kotani[1], Kozo Makiyama[1], Ken Nakata[1]
[1] Transmission Devices Laboratory, Sumitomo Electric Industries, Ltd., Yokohama 244-8588, Japan

Abstract text: N-polar GaN high-electron-mobility transistors (HEMTs) for RF power amplifiers have attracted considerable interest. The reported output power of N-polar GaN HEMTs at W-band are higher than that of Ga-polar GaN HEMTs. When operating at high output power, however, the device generates a lot of heat, which degrades device characteristics. The study of the thermal conductivity of the channel layer, which generates most of the heat in N-polar GaN HEMTs, is crucial for the design of N-polar GaN HEMTs. In this study, the thermal conductivity of channel layer and thermal boundary resistance were calculated by reverse Non-Equilibrium Molecular Dynamics (rNEMD) method using Universal Neural Network Potential (UNNP).

Assuming N-polar GaN HEMT with GaN buffer layer, AlN barrier layer and β-Si_3N_4 passivation layer, the calculation model was created. The thickness of GaN channel layer was 20 times c-axis length, similar thickness of reported N-polar GaN HEMTs. AlN was assumed to be lattice matched to GaN buffer layer. During the simulation, the momenta of the hottest atom in the bottom region and the coldest atom in the center region were exchanged conserving the total energy and momentum. This exchange causes external heat flux. And the heat flux is balanced within the system, causing a temperature gradient and a temperature jump at interfaces. In our simulations, the temperature was set to 300 K, the time step was 1 fs, and the number of steps was 200000. After 2000 step calculation, atoms were exchanged at each 50 steps.

Thermal conductivities of GaN, AlN, and β-Si-$_3N_4$ were estimated to be 18.1, 59.6, and 4.83 W/mK, respectively. Thermal boundary resistances of GaN/AlN and GaN/β-Si_3N_4 interfaces were estimated to be 1.25×10^{-9}, and 1.50×10^{-9} Km^2/W. Our results suggest that the thermal conductivity of the GaN channel layer in N-polar GaN HEMTs is lower than that of bulk GaN due to phonon scattering at the interfaces as the channel layer thickness is less than the phonon mean free path. Furthermore, the influence of the thermal boundary resistance is not negligible as the interfaces are very close to 2DEG channel where heat is generated during device operation. Our findings indicate that heat dissipation techniques are critical for N-polar GaN HEMTs and will pave the way for further improvements.

PC-Tue-P22 - Investigation of electron transport in 2DEG AlGaN/GaN and 3D GaN channels under strong electric field

2. Physics and characterization

Irmantas Kašalynas[1]
Emilis Šermukšnis[1], Linas Ardaravičius[1], Justinas Jorudas[1], Liudvikas Subačius[1]
[1] Center for Physical Science and Technology (FTMC)

Abstract text: Gallium nitride (GaN) is highly promising semiconductor for high-speed, high-power applications due to its wide bandgap (3.4 eV) and high electron saturation velocity (~2.5×10^7 cm/s) [1]. GaN heterostructure-field-effect transistors (HFETs) benefit from high electron drift velocity, lower noise, and slower degradation, particularly at an electron density of 1.0×10^{13} cm^{-2} [2]. This is linked to the resonance decay of hot phonons, which impacts electron transport properties. Determination of the self-heating effects of ohmic contacts and conductive channels recently [3] contributed to better understanding electron transport behaviour in the conductive channels of GaN-devices [4].

In this work we will discuss characteristics of the 2DEG channels in AlGaN/AlN/GaN, AlGaN/GaN and 3D channels in epitaxial GaN obtained experimentally at room temperature by using nanosecond-pulses, measurement techniques which allow minimization of self-heating effects under presence of strong electric fields. The usage of pulsed high current density regime with electric pulses duration as short as 2 ns allowed us to reach maximum electron drift velocities up to ~2.6×10^7 cm/s (@ 220 kV/cm) and ~1.2×10^7 (@60 kV/cm only) for the 3D and 2DEG channels, respectively. We will discuss the differences in electron mobility dependences on electric field and impact of hot-phonon effects which in GaN-type materials are more pronounced in 2DEG than in 3D channels.

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PC-Tue-P23 - High Power Factor Stability Over Wide Low-Temperature Ranges in GaN-Based Two-Dimensional Hole Gas for Thermoelectric Generators

2. Physics and characterization

Lex Pardon[1]
Filipe A. Cardoso[1], Karen M. Dowling[1]
[1] Department of Microelectronics, Delft University of Technology, Delft, The Netherlands

Abstract text: Maintaining a high Power Factor (PF) in thermoelectric generators across wide temperature ranges is a significant challenge, as traditionally doped semiconductors suffer from carrier freeze-out at cryogenic temperatures and excessive intrinsic conduction in high temperatures. This results in a narrow temperature range for optimal operation. GaN/AlGaN based two-dimensional electron and hole gases (2DEG, 2DHG) are inherently formed through polarization of the AlGaN layer, resulting in a carrier density that is largely independent of thermal activation. These 2DEG and 2DHGs have increased hole mobility due to reduced impurity scattering, improving the conductivity and, therefore, the PF over doped GaN. Previous studies have demonstrated the thermoelectric potential of AlGaN/GaN 2DEGs [1-2]. However, for a complete thermoelectric device, a complementary 2DHG may further improve efficiency.

A GaN/AlGaN/GaN double heterojunction structure based on previous 2DHG studies [3, 4] was optimized for PF through simulations using sheet density extracted from Nextnano. The selected film stack was grown at DOWA Electronics Materials, then Ni/Au ohmic contacts were deposited using metal evaporation. A sheet resistance ranging from 70 to 120 kΩ/□ was measured in a cryogenic environment from 50 to 300K, confirming the presence of a polarization-induced 2DHG. However, a discrepancy of 3.5 times was observed between the simulated and measured sheet resistance values, suggesting that additional scattering mechanisms may be reducing the overall mobility of the 2DHG. Furthermore, a Seebeck coefficient of 100 to 200 μV/ΔK was measured by creating a 20 K temperature gradient with temperatures ranging from 70 to 300 K. The resulting PF is estimated to be 60−100 $\mu Wm^{-1}K^{-2}$ over a temperature range of 70 to 300 K, demonstrating a stable PF across a wide temperature, which may provide pathways for GaN based TEGs for microelectronics in extreme environments, such as deep space exploration.

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PC-Tue-P24* - AlGaN/GaN MIS-HEMT Kink Effect Attribution to Poole-Frenkel Effect Through Device Topology Analysis

2. Physics and characterization

Arthur Collier[1]
Wesley Sampson[2], Abdalla Eblabla[1], Richard Hammond[2], Sinan Goktepeli[2], Khaled Elgaid[1]
[1] Centre for High Frequency Engineering, Cardiff University. Cardiff, UK
[2] IQE PLC, Cardiff, UK

Abstract text: AlGaN/GaN HEMTs are beginning to play a dominant role for RF power amplifier applications such as 5G and beyond, phased array radar, and satellite communications due to high efficiency and high-power density at mm-wave frequencies. However, efficiency and reliability are limited by trapping effects arising from the trap states under the gate, and in the buffer, channel, and barrier. A notable symptom of these trap states is a kink in drain-source current (I_{ds}), which occurs due to de-trapping during a forward sweep of drain-source voltage (V_{ds}). The origin of the kink effect has been attributed to both impact ionisation [1] and the Poole-Frenkel effect [2]. With multiple physical origins in literature, this work introduces new insights into the influence of topology on the kink effect, such as variations in the drift region and gate field plates (GFP).

AlGaN/GaN MIS-HEMTs were fabricated on a 200 mm diameter GaN-on-Si wafer. Measurements were conducted on devices with 1 µm gate length (L_g), 20 µm gate width (W_g), 1 gate finger, 1 µm source-gate spacing (L_{sg}), while drain-gate spacing (L_{dg}) was varied from 1 – 15 µm. During DC-IV characterisation, an I_{ds} kink was observed above a certain V_{ds} during the forward sweep. This indicated de-trapping, resulting in reduced virtual gating effects and therefore an increased I_{ds}. The kink was not observed in the reverse sweep as the traps were unable to re-fill due to the high electric field. When observing I_{ds} as a function of V_{gd}, the kink peak voltage (V_{Kink}) was constant as V_{gs} varied, indicating gate-drain electric field dependency. On devices with varying L_{gd}, a linear relationship between V_{Kink} and L_{gd} was observed, confirming that the primary location of traps causing the kink effect was between the gate and drain. The electric field dependency was further confirmed by the inclusion of a GFP, where redistribution of the electric field between the gate and drain resulted in kink mitigation. Therefore, the dominant mechanism for trap release for these devices was identified as the Poole-Frenkel effect, evidenced by the dependence on electric field between the gate and the drain.

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PC-Tue-P25* - Optical properties of cubic InGaN for the entire In composition range

2. Physics and characterization

Jonas Rose[1]
Elias Kluth[2], Elias Baron[2], Rüdiger Goldhahn[2], Silas A. Jentsch[3], Mario F. Zscherp[3], Sangam Chatterjee[3], Jörg Schörmann[3], Martin Feneberg[2]
[1] Institut für Physik, Otto-von-Guericke-Universität Magdeburg, Magdeburg, Germany & Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V, Berlin, Germany
[2] Institut für Physik, Otto-von-Guericke-Universität Magdeburg, Magdeburg, Germany
[3] Institute of Experimental Physics I and Center for Materials Research, Justus Liebig University Giessen, Giessen, Germany

Abstract text: Cubic $In_xGa_{1-x}N$ (c-InGaN) is a promising material for fabricating highly efficient opto-electronical devices and can potentially replace its hexagonal counterpart for certain applications. Due to the lack of internal polarization fields [1] originated in higher crystal symmetry and lower band gap energies c-InGaN is a suitable candidate for applications in the visible spectrum. Especially InGaN/GaN quantum wells can be used for green light-emitting devices [2]. Therefore, the knowledge of its optical properties is of special interest. Recent advancements in crystal growth have led to improved structural quality and expanded the range of In-content ($0 \leq x \leq 1$) enabled by the incorporation of strain, marking signifcant progress in this field [3].
We describe our investigation of c-InGaN thin films grown via plasma-assisted molecular beam epitaxy (MBE) on c-GaN/AlN/3C-SiC/Si substrates oriented in the (001) direction. Through spectroscopic ellipsometry analyses spanning the infrared (IR) and visible-ultraviolet (VIS-UV) spectrum, we extract the dielectric function, which contains contributions from phonons, plasmons, and interband transitions. Ellipsometry is an optical technique with high sensitivity to thin layers, allowing non-destructive and contact-free characterization, measuring the change of polarization between an incident light
beam and the light reflected from the sample. Moreover, we consider many-body effects like band gap renormalization and Burstein-Moss shift affecting the transition energy between valence and conduction band as well as strain-induced alterations in the absorption edge. From this, the fundamental band gap energies and a bowing parameter of $b = 1.61$ eV can be determined.

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PC-Tue-P26 - Role of electronic degrees of freedom in In incorporation during MOVPE - ab initio explanation

2. Physics and characterization

Pawel Kempisty[1]
Ahsfaq Ahmad[1], Pawel Strak[1], Konrad Sakowski[2], Anna Kafar[1], Jacek Piechota[1], Stanislaw Krukowski[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142 Warsaw, Poland
[2] Institute of Applied Mathematics and Mechanics, University of Warsaw, 02-097 Warsaw, Poland

Abstract text: Indium incorporation on the GaN(0001) surface is studied by ab initio calculations for the conditions corresponding to InGaN growth by Metal Organic Vapor Phase Epitaxy (MOVPE). To understand phenomena at the atomic level, the calculations based on Density Functional Theory (DFT) and the thermodynamic analysis of the surface processes has been performed. The processes on the terraces on vicinal GaN (0001) surface are calculated. It is assumed that the atomically flat faces are covered fully by NH_3/NH_2 species. The *ab initio* results indicate that the adsorption energy strongly depends on the electronic properties of the surface. Adsorption energy varies from -10.0 eV for NH_2 covered (x = 0) to -3.0 eV for mixed 0.69 NH_2 + 0.31 NH_3 covered (x = 5/6 ML) surface. This change is related to Fermi level position which is moved from location within valence band, across the bandgap up to within conduction band. The Fermi energy position determines the occupation of quantum states at the surface therefore it controls the energy gain during adsorption of indium due to electron transfer to the newly emerging states. Furthermore, full thermodynamic analysis was made showing additional, much smaller, contribution from the vibrational degrees of freedom to free energy. Combination of these factors induced an increase of In equilibrium pressures related to hydrogen pressure increase that is correlated with high coverage by ammonia molecule. The results prove that the drastic reduction of the indium incorporation into InGaN layers during MOVPE growth under the conditions of small amount of hydrogen in the vapor is a consequence of hydrogen influence on In adsorption processes.

PC-Tue-P27 - Confocal resonant Raman scattering and photoluminescence in thick InGaN layers

2. Physics and characterization

Daqi Wang[1]
Zhizhong Chen[1], Fei Huang[1], Zuojian Pan[1], Chuhan Deng[1], Haodong Zhang[1], Yian Chen[1], Boyan Dong[1], Yuchen Li[1], Ling Hu[1], Mengqing Hua[1], Lvyun Chen[1], Yiran Wu[1], Weihua Chen[1], Fei Jiao[1], Xiangning Kang[1], Qi Wang[2], Bo Shen[1]
[1] State Key Laboratory for Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China
[2] Dongguan Institute of Optoelectronics, Peking University, Dongguan, Guangdong 523808, China

Abstract text: Thick InGaN layer as an active region may increase the growth temperature because it requires a lower average In content, which is advantageous for high efficiency and low spectral shift in long-wavelength LEDs. Composition, strain, and defects in InGaN critically impact luminescence. Raman scattering (RS) is a sensitive, local, nondestructive, and rapid method for characterizing composition, strain, and defects in III-V alloys. However, due to GaN's superior crystal quality and greater thickness, the Raman signal mainly originates from GaN. Unlike conventional RS, resonant Raman scattering (RRS) involves transitions to real rather than virtual states, enhancing Raman intensity.[1]

After growing green QWs on GaN templates, thick InGaN layers (25–260 nm) were deposited, with the In content increasing from 10% to 20%, as shown in Figure 1. Confocal Raman and PL spectral mapping revealed that the intensity of the A_1(LO) mode increased with increasing thickness of the InGaN layers. When the growth time exceeded 1800 s, red and blue-violet emissions appeared due to InGaN phase separation and compositional fluctuation. Figure 2 presents the Raman A_1(LO) peak position and PL spectra of the blue light peak in the 260 nm InGaN sample.The opposite trends of the blue light wavelength and the Raman peak position suggest that stress relaxation enhances In content incorporation, leading to lattice expansion and a redshift of the resonance peak.

To determine In content, strain, and structural properties, TEM, EDX, and XRD RSM measurements were conducted. Based on the strain and In content of the InGaN matrix, the resonant frequency of InGaN A_1(LO) was calculated, as shown in Table 1. The probability was considered as the sum of intensities from all possible processes, including outgoing, incoming, double resonant processes. Results confirmed that increased thickness leads to more electronic energy levels, additional resonance pathways, and enhanced intensity. The A_1(LO) phonon scattering intensity was calculated using electronic energy levels extracted from PL spectra, showing good agreement with experiments. Combined with the confocal mapping measurements and the calculation results, the resonance mechanism of RRS in thick InGaN alloys was demonstrated, as shown in Figure 3.

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Selected references

PC-Tue-P28 - Impact of Growth Temperature on the Emission Properties of Zincblende InGaN/GaN Quantum Wells

2. Physics and characterization

Daniel Dyer[1]
Menno J. Kappers[2], David J. Wallis[3], Rachel A. Oliver[2], David J. Binks[1]
[1] Department of Physics and Astronomy & Photon Science Institute, University of Manchester, Manchester, M13 9PL, UK
[2] Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, CB3 0FS, UK
[3] Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, CB3 0FS, UK and Centre for High Frequency Engineering, Cardiff University, Cardiff, CF24 3AA, UK

Abstract text: Efficient longer wavelength emitters are crucial for the next generation of display applications. Current commercial light-emitting diodes (LEDs) – utilising wurtzite (wz) InGaN/GaN quantum wells (QWs) as the active layer – experience a significant efficiency reduction as the emission wavelength is increased. The efficiency reduction is associated with a greater indium concentration strengthening the polarisation field across the QWs [1], and the lower growth temperatures leading to a higher density of non-radiative point defects in the material [2]. Zincblende (zb) LEDs are an alternative for longer wavelength emitters due to the lack of polarisation fields along the (001) direction [3]; its intrinsically lower bandgap leading to higher QW growth temperatures compared to current commercial LEDs [4].

Molecular beam epitaxy grown zb-InGaN/GaN QWs have been shown to emit across the visible spectrum at low temperature [5]. However, growth by metal-organic chemical vapor deposition (MOCVD) is crucial to enable large scale manufacturing of zb LED devices. Blue-emitting MOCVD-grown zb-QWs have been reported previously, exhibiting rich microstructural features [6] that can influence the emission properties [7]. Thus, it is crucial to understand how QW growth temperature affects the emission properties beyond this wavelength.

Here we report emission from zb-InGaN/GaN QWs that can be tuned from the blue to the orange spectral region by reducing the QW growth temperature, consistent with increasing indium content within the QW layers. A reduction in thermal quenching can be observed as the growth temperature of the QW layer decreases, consistent with a reduction in thermionic escape from the zb-QWs – reported to limit emission efficiency of zb-QWs at room temperature [8] – due to the higher energy barrier to escape caused by the increased indium content within the QW layers.

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PC-Tue-P29* - Exciton Dynamics in Two-Dimensional Hybrid Structures based on an InGaN Quantum Well coupled to a MoSe2 Monolayer

2. Physics and characterization

Danxuan Chen[1]
Delphine Lagarde[2], Louka Hemmen[2], Laurent Lombez[2], Pierre Renucci[2], Maxime Mauguet[2], Lei Ren[2], Cedric Robert[2], Nicolas Grandjean[1], Xavier Marie[3]
[1] Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland
[2] Université de Toulouse, INSA-CNRS-UPS, LPCNO, 135 Avenue Rangueil, 31077 Toulouse, France
[3] Université de Toulouse, INSA-CNRS-UPS, LPCNO, 135 Avenue Rangueil, 31077 Toulouse, France; Institut Universitaire de France, 75231 Paris, France

Abstract text: Hybrid structures combining III-nitride and transition metal dichalcogenide semiconductors offer strong potential for light harvesting and optoelectronics. In this work, we investigate the properties of a hybrid system composed of a $MoSe_2$ monolayer (ML) coupled to a surface InGaN/GaN quantum well (QW), with their coupling controlled by a thin top barrier of variable thickness. Time-integrated and time-resolved (TR) micro-photoluminescence (PL) measurements reveal that the QW exciton emission is increasingly quenched as the barrier thickness, d, decreases, with a 3-fold reduction in PL intensity for d = 1 nm due to carrier transfer to the $MoSe_2$ ML. This interaction is further confirmed by TR-PL spectroscopy, showing a clear reduction in QW exciton lifetime. Interestingly, excitonic transport in the QW is affected, as indicated by a decrease in exciton diffusion length in the presence of the $MoSe_2$ ML. Temperature-dependent PL measurements highlight the role of localization effects in the QW. The results can be well interpreted by a type-II band alignment between the InGaN QW and the $MoSe_2$ ML, with carrier transfer facilitated by a defect-assisted tunnelling process. The control of QW exciton lifetime and diffusion length induced by proximity effects with a 2D material could offer new perspectives for optoelectronic applications.

PC-Tue-P30* - Comparison of metal-modulated and conventionally grown cubic, red emitting InGaN bulk layers and InGaN/GaN quantum wells

2. Physics and characterization

Silas A. Jentsch[1]
Mario F. Zscherp[1], Markus Stein[1], Matthew Chia[2], Donat J. As[3], Sangam Chatterjee[1], Jörg Schörmann[1]
[1] Institute of Experimental Physics I and Center for Materials Research, Justus-Liebig-University Giessen, Giessen, Germany
[2] Department of Physics, Cambridge University, Cambridge, United Kingdom
[3] Department of Physics, University Paderborn, Paderborn, Germany

Abstract text: Cubic InGaN alloys are a promising candidate material for next-generation optoelectronic applications like red micro light-emitting diodes (μ-LEDs) as they lack internal fields and promise to cover large parts of the electromagnetic spectrum from the deep UV towards the mid-infrared. Therefore high-quality epitaxial growth of cubic InGaN is essential. However, the growth of indium-bearing nitride quantum wells in the metastable cubic phase still poses many challenges. Here, we apply a metal-modulated growth approach [1] to improve the morphological and structural properties of the epitaxially grown nitride films.

We report cubic InGaN bulk layers, multi and single InGaN/GaN quantum wells (x(In) = 0.33-0.27) grown by metal-modulated molecular beam epitaxy on c-GaN/AlN/3C-SiC/Si templates [2]. For this metal-modulated epitaxy we alternately open the Ga and In shutter while constantly supplying nitrogen from the plasma source. With this approach it is possible to grow InGaN/GaN quantum well structures as well as fully alloyed “bulk-like” c-InGaN layers just by adjusting the t_{In+N} shutter duration. These metal-modulated grown films are compared to conventionally grown cubic InGaN films, demonstrating superior properties of the metal-modulated grown samples. High-resolution X-ray diffraction (HR-XRD) reveals the excellent structural properties of the metal-modulated approach with a higher cubic phase purity of the c-InGaN layers. Atomic force microscopy and scanning electron microscopy analyze the morphology of the layers. Complementary time-resolved, temperature dependend and power dependend photoluminescence studies elucidate the effect of strain, In content and quantum confinement on the optical response of c-InGaN layers. All grown samples exhibit red emission, underscoring the potential of cubic InGaN for high-efficiency optoelectronic devices.

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PC-Tue-P31* - Bayesian Analysis of Time-Resolved Photoluminescence in Indium Gallium Nitride Quantum Wells: Evidence of Compressed/Stretched-Exponential Behavior

2. Physics and characterization

Kazunori Iwamitsu[1]
Itsuki Shimbo[2], Zentaro Akase[1], Toshiya Yokogawa[1], Atsushi A. Yamaguchi[2], Shigetaka Tomiya[1]
[1] Nara Institute of Science and Technology, Nara, Japan
[2] Kanazawa Institute of Technology, Ishikawa, Japan

Abstract text: Achieving high-performance GaN-based optical devices requires a precise understanding of carrier dynamics. Temperature-dependent time-resolved photoluminescence spectral imaging (TRPL-SI), which simultaneously captures emission wavelengths and decay curves, serves as a powerful technique for this purpose. TRPL decay curves are typically analyzed using double-exponential (DE) decay models or compressed/stretched-exponential (CE/SE) decay models. Given the complexity of carrier dynamics in indium gallium nitride (InGaN) quantum wells (QWs), arising from defects and composition fluctuations, a rigorous analytical approach is essential. Consequently, the selection of an appropriate model and the quantitative evaluation of its fitting parameters are critical for accurately interpreting the acquired data.

In this study, we measured the TRPL-SI of an $In_{0.24}Ga_{0.76}N$ single quantum well (SQW) with an emission wavelength range of 420–480 nm and a time window of approximately 9.5 ns. The temperature dependence from 2 K to room temperature was analyzed using Bayesian inference, which enables quantitative parameter evaluation and ensures data reproducibility through posterior probability distributions. The analysis revealed that the CE/SE model provided higher estimation accuracy and narrower credible intervals than the DE model, suggesting that CE/SE fitting is more suitable for discussion. Furthermore, the average lifetime obtained increased as the photon energy decreased, while the CE behavior was exhibited. This distinctive behavior varied with temperature, suggesting its association with specific fast carrier trapping sites. In our presentation, we will further explore these modeling differences, the temperature dependence of the average lifetime, and the implications of this unique carrier dynamics behavior.

PC-Tue-P32* - Photoluminescence excitation wavelength dependency of blinking phenomena in InGaN/GaN single quantum well

2. Physics and characterization

Kotaro Oikawa[1]
Ruggero Micheletto[1]
[1] Yokohama City University, Yokohama, Kanagawa, Japan

Abstract text: InGaN optical devices have emission wavelengths that cover the entire visible light range, depending on the In composition ratio. However, the high concentration of In samples (green color) contains a large amount of defects and impurities, so there are still issues regarding highly efficient luminescence. InGaN/GaN has been reported to have non-uniform luminescence due to defects and impurities. Blinking has also been reported as a temporal instability of the photoluminescence (PL) intensity. Although the mechanism of the blinking phenomenon has not yet been clarified, a qualitative explanation is that it is related to the localization of excitons due to the quantum well structure. In this study, we performed time-resolved PL measurements by simultaneous excitation of the well and barrier layers as well as by selective excitation of the well layer only, and further showed that the blinking point size varies with the excitation wavelength by statistical analysis of the continuous PL images obtained. Specifically, InGaN/GaN bulk with an emission wavelength of 510 nm was excited at each wavelength, and PL images were recorded in real time (30 fps) by a CMOS camera. Then, we investigated the influence of the excitation condition of each layer on the blinking phenomenon from the time-averaged and standard-deviation maps of the continuous PL images. While a large number of blinking points were observed in the ultra violet excitation (365 nm) as in the previous study, a clear reduction in the size and disappearance of blinking points were observed in the violet excitation (430 nm). The decrease in the blinking points is considered to be caused by the selective excitation of the InGaN layer, which leads to a stable recombination process in the quantum wells. In addition, we conducted PL spectral measurements at different excitation wavelengths. From the comparison of their PL spectra, it was found that the excitation (absorption) of the GaN layer in ultra violet excitation is supported, indicating that the excited state of the GaN layer is involved in the blinking phenomenon in InGaN. Furthermore, we indicate that the influx of carriers from the GaN layer to the InGaN layer is responsible for the localized intense luminescent centers and suggest that these carriers provide the recombination for the blinking phenomenon.

PC-Tue-P33* - Low and high frequency noise investigation from micro to macro scales in InGaN light-emitting diodes

2. Physics and characterization

Danylo Bohomolov[1]
Vita Ivanova[2], Oliver Liu[1], Conny Becht[1], Grzegorz Muziol[3], Mateusz Hajdel[3], Ulrich T. Schwarz[1]
[1] Institute of Physics, Chemnitz University of Technology, Chemnitz, Germany
[2] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
[3] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: Noise characterization for light-emitting diodes (LEDs) can serve not only as a reliability indicator [1], but also provide information on defects in the active region [2]. Defects randomly modulate the free charge carrier number and, therefore, lead to (optical) fluctuations in the photon number [3]. The role of defects can be directly observed in microscopic regions of emission surface in so-called blinking effect [4].

To investigate the relationship between microscopic blinking and noise in macroscopic scale, i.e. noise of the whole LED, we changed gradually the explored area with cross-sections ranging from 0.16 µm to 300 µm for measuring corresponding optical noise at different current densities. At low frequencies (< 1 kHz), the appearance of generation-recombination (GR) noise from the smallest areas was observed with subsequent increase of its amplitude. The trend of the Lorentzian shift toward higher frequencies with increasing current remained unchanged as the cross-section increased to 38 µm. However, starting from a spot diameter of 75 µm, the low-frequency component in the form of $1/f^{\gamma}$ began to dominate over the GR term, which is characteristic of the macroscopic noise of the entire LED [5].

This behavior aligns well with the proposed noise component model, where the low-frequency component $1/f^{\gamma}$ results from the superposition of individual GR components with a uniform distribution of relaxation lifetimes in the case of a wide-range distribution. In the case of a narrow distribution, it becomes similar to a single GR term, as observed on microscopic scales.

In summary, the approach with transitioning from micro to macro scale, demonstrated for the first time, confirmed the generation-recombination origin of low-frequency noise in InGaN LEDs, which might assist in investigating trap characteristics in the active region of the device.

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PC-Tue-P34 - Stress and doping analysis of low n-doped GaN layers grown on GaN, silicon and sapphire substrates by micro-Raman

2. Physics and characterization

Ndembi Ignoumba-Ignoumba[1]
Camille Sonneville[1], Adrien Bidaud[2], Mohammed El Amrani[3], Thibaud Guillemin[4], Maroun Dagher[5], Vishwajeet Maurya[3], Florian Bartoli[4], Eric Frayssinet[4], Farid Medjdoub[2], Julien Buckley[3], Yvon Cordier[4], Matthew Charles[3], Dominique Planson[1], Cyril Buttay[1]
[1] Univ. Lyon, INSA Lyon, Univ. Claude Bernard Lyon 1, Ecole Centrale Lyon, CNRS, Ampère, F-69621, France.
[2] I.E.M.N – CNRS, 59652 Villeneuve d'Ascq, France.
[3] Univ. Grenoble Alpes, CEA-LETI, Grenoble 38000, France.
[4] Université Côte d'Azur, CNRS, CRHEA, F-06560 Valbonne, France.
[5] INSA Lyon, Ecole Centrale de Lyon, CNRS, Université Claude Bernard Lyon 1, CPE Lyon, INL, UMR5270, 69621, Villeurbanne, France.

Abstract text: Vertical GaN power devices counters the drawbacks of the lateral ones. The best performances are observed with vertical GaN-on-GaN, but the absence of large GaN substrates makes the homoepitaxy option less marketable than the heteroepitaxy one. However, thick heteroepitaxial GaN drift layers must exhibit a low biaxial stress and a low n-doping density. Monitoring these properties of GaN layers are therefore crucial issues for vertical GaN power devices development. Here, a methodology is proposed, using non-destructive micro-Raman, to analyze biaxial stress and n-doping density for low n-doped GaN layers ($< 10^{17}$ cm^{-3}) independently of the substrate type (GaN, silicon and sapphire).

The variation of A_1(LO) and E_2^H GaN Raman shifts (ω_{A1}, ω_{E2}) due to biaxial stress ($\boldsymbol{\sigma_B}$) and the n-doping density (**n**) is $\Delta\omega_{A1} = K^B_{A1} \times \boldsymbol{\sigma_B} + f(\mathbf{n})$ and $\Delta\omega_{E2} = K^B_{E2} \times \boldsymbol{\sigma_B}$. Combining these two equations, ω_{A1} can be linearly correlated to ω_{E2}, with a slope ($S=K^B_{A1}/K^B_{E2}$) independent of the biaxial stress and a y-intercept g(**n**) increasing with **n**. Micro-Raman 2D-mapping shows that samples display the expected behavior concerning the biaxial stress: GaN-on-sapphire layers exhibit the highest values of the ω_{A1} and ω_{E2} (compressive stress) while GaN-on-silicon layers have the lowest ones (tensile tress). In addition, results agree with the proposed relationship between ω_{A1} and ω_{E2}, such that regardless of the substrate, the slope S is similar. Hence, this work refines S to 0.78 ± 0.03, compared to the literature (0.28 to 0.80 [1,2]). Moreover, as expected, the y-intercept increases with the sample n-doping level, regardless of its substrate. Present results can then be used as a benchmark for estimating n-doping level and inhomogeneity of low n-doped GaN layers.

This study shows that micro-Raman is an effective technique for analyzing the low doped and low strain layers required for the next generation of vertical GaN power devices. Furthermore, the final publication will correlate these micro-Raman results with other electrical and physical characterizations.

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PC-Tue-P35 - Low-frequency noise components modelling in InGaN light-emitting diodes

2. Physics and characterization

Vita Ivanova[1]
Danylo Bohomolov[2], Oliver Liu[2], Conny Becht[2], Grzegorz Muziol[3], Mateusz Hajdel[3], Ulrich T. Schwarz[2]
[1] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
[2] Institute of Physics, Chemnitz University of Technology, Chemnitz, Germany
[3] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: Fluctuations of light-emitting diodes (LEDs) emission are undesirable for the effective and reliable application. However, the study of LED noise in the low-frequency region provides information not only on the device performance, but also on the presence of defects in their structure [1, 2, 3, 4, 5].

Based on experimental results, we introduce a semi-empirical model which includes the low-frequency component in the form of *1/f*ᵞ, generation-recombination (GR) components, and white noise. The noise components are analyzed using a statistical approach. The physical nature of the origin of the GR noise is discussed, and the dominant role of defects as traps in the active region in forming GR noise is shown. The energy distribution and the occupancy of the trap levels determine the corresponding distribution of the relaxation lifetimes of the charge carriers. The latter, in turn, determines the result of the superposition of all GR components.

The experimental data are found to be best fitted by a uniform distribution of relaxation times, which acts either in a wide range resulting in *1/f*ᵞ or a narrow one leading to a single GR Lorentzian. The possible negative Lorentzian amplitude caused by e-h correlated GR processes [6] was also included.

The proposed model also describes fluctuations in emission in microscopic regions where the dominant influence of a limited group of defects, can be observed, i.e., blinking [7]. The transition to macroscopic scales in this analysis demonstrates that the simultaneous effect of a large number of traps can result in several superpositions of GR components with different distributions.

The proposed representation of the noise components demonstrates good agreement with experimental data at both the micro and macro scales, which can help to understand the role of defects in the formation of noise in InGaN LEDs.

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PC-Tue-P36* - Low-frequency local fluctuations of light emissions in InGaN light-emitting diodes

2. Physics and characterization

Oliver Liu[1]
Danylo Bohomolov[1], Vita Ivanova[2], Conny Becht[1], Grzegorz Muziol[3], Mateusz Hajdel[3], Ulrich T. Schwarz[1]
[1] Institute of Physics, Chemnitz University of Technology, Chemnitz, Germany
[2] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
[3] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: Defects in the active region reduce efficiency of light emitting diodes (LEDs), have an impact on long-term reliability, and cause fluctuations of the emitted light intensity, resulting in light intensity noise. These optical instabilities may appear as small blinking spots inside the region near defects [1, 2, 3]. We investigated these local intensity fluctuations and their dependence on temperature and current in InGaN LEDs by using micro-electroluminescence to investigate the power spectral density (PSD) of the time-resolved blinking intensity. In contrast to prior studies of macroscopic fluctuations of light emissions [4], in which it can be difficult to distinguish the influence of a separate small group of defects, the individual local blinking spot shows a distinct Lorentzian-type PSD of the generation-recombination (GR) noise.

With increasing current, we observe an acceleration of the blinking processes, indicated by a shift of the Lorentzian peak to the higher frequencies with new ones forming in the lower frequencies. This behavior is smooth for small (~0.1 A/cm^2) current densities and shared across different blinking points. Larger (~1 A/cm^2) variation in current density result in appearance and disappearance of Lorentzian peaks, indicating that blinking frequencies enter and exit the time window of the experiment. Similar results were seen when the temperature was increased, in which rising temperatures lead to an increase in speed of the blinking areas. To investigate this further, we also used a sCMOS camera to plot a map of the standard deviation of pixel intensity across the camera image. The resulting maps show that at low currents only a few blinking spots are active, which increase in number and form clusters when the current is increased.

In summary, our measurements show, that through the combined use of spatially resolved measurements and noise analysis, we may be able to better understand the underlying microscopic mechanics of the optical fluctuations of InGaN LEDs.

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PC-Tue-P37* - Polarisation-resolved cathodoluminescence study of a zincblende InGaN/GaN single quantum well

2. Physics and characterization

X. Xu[1]
M. Frentrup[1], G. Kusch[1], Z. S. Pehlivan[1], M. J. Kappers[1], D. J. Wallis[1], R. A. Oliver[1]
[1] University of Cambridge

Abstract text: Zincblende (zb) InGaN micro-LEDs have the potential to overcome the low efficiency of long-wavelength emission for devices in the conventional wurtzite phase, as (001) zb GaN is free of spontaneous and piezoelectric polarization fields and has a narrower bandgap compared to wurtzite GaN [1]. However, zb InGaN suffers from a high density of stacking faults (SFs), which impacts the luminescence properties. Furthermore, optical characteristics typical of quantum wires (QWires) were recently identified in the cathodoluminescence (CL) of a zb InGaN single quantum well (SQW) sample, attributed to indium enrichment at SF locations [2]. Photoluminescence studies suggested that the QW emission is polarised and may relate to such SF-related QWires [3].

In this presentation, we will report on polarisation-resolved CL measurements of zb InGaN SQW samples with different SF density. The samples were grown on zb GaN buffers with thicknesses varying from 600 nm to 3000 nm by metal-organic vapour phase epitaxy. X-ray diffraction analysis shows that the SF density reduces with buffer thickness and hence a reduction in polarisation might be expected [4]. However, the mean spectra of panchromatic CL maps show that the SQW emission is highly polarised. Polarisation-resolved panchromatic CL maps show that the polarised light arises from both SF-rich and defect-free regions, but the majority of it is from regions with no obvious relation to SFs. However, elongated features reminiscent of QWires were observed in the panchromatic CL maps at SF locations. The wire-like features were oriented along perpendicular directions in CL maps in which the polarization was in perpendicular orientations, supporting the suggestion that QWires can generate polarised light. The degree of polarisation (DoP) of about 0.625 for the SQW emission is approximately independent of the SF density. If the polarisation was largely related to the QWires, the reduction in SF density with buffer thickness would lead to a lower DoP at larger thicknesses. Hence, this provides further evidence that most of the polarised emission is attributable to defect-free material.

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PC-Tue-P38* - Carrier localization in long-wavelength emitting InGaN quantum-wells

2. Physics and characterization

Xiaoping Zhou[1]
Yan Li[1], Ran Yao[1], Hua Yang[1], Xiaoyan Yi[1], Junxi Wang[1], Jinmin Li[1]
[1] Research & Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

Abstract text: The localization of carriers is critical to the dislocation screening in the nitrides. The InGaN based yellow light-emitting diodes are systematically characterized by temperature-dependence electroluminescence by different forward currents. At low injection condition, the temperature dependence of the peak energy shows a “V” shape, different to the tendency described by the Varshni equations. As the injection current increasing, the shape becomes an “inverted V” gradually. The temperature dependence of the full width at half maximum shows a scoop shape. Scanning electron microscopy, transmission electron microscopy and Raman spectroscopy are utilized to analyze the composition fluctuation, well width fluctuation and the dislocations in the quantum well. The well width is the dominant factor to the localization in long-wavelength quantum. The degree of localization in electron and hole is different, which also plays a role in the special temperature dependence. The investigations of the mechanism origin of the carrier localization lay the foundation for the design and fabrication of the InGaN based long wavelength light-emitting diodes.

PC-Tue-P39* - Direct observation of anisotropic lateral ambipolar diffusion of charge carriers in a blue InGaN single quantum well on freestanding GaN

2. Physics and characterization

Conny Becht[1]
Ulrich T. Schwarz[1], Thomas F.K. Weatherley[2], Nicolas Grandjean[2]
[1] Institute of Physics, Chemnitz University of Technology, Chemnitz, Germany
[2] Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Abstract text: In InGaN quantum wells (QW) the diffusion length was shown to be on the order of a few micrometers, despite the common image of strong carrier localization effects on a nanometer scale [1, 2, 3]. The lateral ambipolar diffusion of charge carriers depends on carrier lifetime [1] and temperature [4]. Here we show that the diffusion is also a function of space and an anisotropic behavior along step edges can be observed.

Micro-photoluminescence (μPL) analysis is done to investigate the anisotropy of carrier diffusion in a blue 2.4 nm single QW on freestanding GaN. The study is done by recording sCMOS images and videos of the PL spot, looking at the spatial distribution change induced by temperature and charge carrier density variations. The PL measurements are correlated with atomic force microscopy (AFM) scans.

At 5 K and low excitation power, the PL spot shows an elongated shape. The elliptic form depends on temperature, excitation power and excitation position. The deformation is attributed to the anisotropic diffusion of carriers. To understand the underlying reason behind the asymmetric distribution of carriers, AFM and μPL studies are combined. Step-edges formed at the growth process are visible in the AFM scan. These steps lead to alternating higher and lower energy potential, and carriers diffusing parallel along the orientation of the steps are less restricted than carriers moving perpendicular to them. The spatial resolution of our μPL setup is too low to detect any step-edges, hence, the AFM scan is used to obtain the direction of the steps, while the sample with the same orientation is placed below the μPL setup. The elongation of the PL spot matches the direction of the steps obtained from AFM.

When temperature or excitation increases, a smoothening of the PL spot is observed, until a circle-like shape is obtained. This is attributed to the additional energy that the carriers are given. Besides, moving the excitation spot over the sample shows a clear change of the PL spot, indicating that diffusion of carriers changes according to the potential landscape of the sample.

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PC-Tue-P40* - Optimisation of micropattern geometry for efficiently emitting InGaN quantum wells

2. Physics and characterization

Adam Brejnak[1]
Conny Becht[2], Zhaozong Zhang[3], Łucja Marona[1], Ryota Ishii[3], Szymon Grzanka[1], Piotr Perlin[1], Mitsuru Funato[3], Yoichi Kawakami[3], Ulrich Theodor Schwarz[2], Anna Kafar[1]
[1] Institute of High Pressure Physics PAS, 01-142 Warsaw, Poland
[2] Chemnitz University of Technology, 09111 Chemnitz, Germany
[3] Kyoto University, 615-8510 Kyoto, Japan

Abstract text: Nitride semiconductor micro-LEDs are currently one of the most intensively studied technological directions in nitride optoelectronics. They are ideal for applications in small displays, such as smartwatches. In this work, we explore the enhancement of light emission intensity from InGaN quantum wells by growing them on dedicated patterned substrates, designed to match the size of future micro-LEDs.

We pattern GaN substrate prior to epitaxial growth using binary or multilevel photolithography to create 3D photoresist structures and then dry etching. After MOVPE growth on these substrates, we observe formation of a c-plane plateau at the top of each structure which shows higher emission intensity than the surrounding.

In this study, we systematically investigate a wide range of structure shapes and epitaxial designs to gain a deeper understanding of the mechanisms responsible for the enhanced emission in the plateau region. We create half-spherical and half-cylindrical structures with widths ranging from 5 to 60 μm and heights between 0.5 and 4 μm. We fabricated three samples differing by the thickness of an InGaN underlayer (10, 50, and 90 nm) below the quantum wells.

We observe several geometry-related effects in our samples. Firstly, the sample with 90 nm InGaN layer shows much higher emission intensity which is probably related with curing defects in the structure. Next, the diameter of the plateau is rather determined by the initial size of the structure than the thickness of the underlayer (so also the total growth time). We observe an optimal height of the structure corresponding to the highest emission intensity of the plateau region between 2 and 3 μm. For the structures with big diameters, the intensity increase in the plateau is clearly smaller.

Our findings provide valuable insights into the role of patterned substrates in enhancing the emission properties of InGaN quantum wells, paving the way for optimized designs in future micro-LED applications.

PC-Tue-P41* - Optical Characterization of Thin-Film InGaN-Based Edge-Emitting Lasers

2. Physics and characterization

Wai Yuen Fu[1]
Yuk Fai Cheung[1], Hoi Wai Choi[1]
[1] Department of Electrical and Electronic Engineering, the University of Hong Kong, Hong Kong, China

Abstract text: InGaN-based semiconductor lasers operating in the visible spectral range have become pivotal components across a wide array of technological applications, encompassing solid-state lighting and optical data storage, as well as emerging fields such as visible-light communications, quantum optics, and optical sensing. While substantial progress has been achieved with vertically emitting (VCSEL) and whispering-gallery mode (WGM) microdisk lasers, edge-emitting laser geometries remain particularly attractive for photonic integrated circuits due to their intrinsic compatibility with waveguide-based photonic platforms. Our recent work demonstrated electrically-injected InGaN-based microdisk lasers fabricated on a thin-film platform, achieving record-high Q factors exceeding 10,000 through optimized optical confinement and improved quantum efficiency [1]. Building upon this established thin-film technology, we extend our investigations to edge-emitting lasers fabricated with rectangular cavity geometries, aiming to exploit their inherent suitability for planar photonic integration and systematically explore their optical performance and resonant mode characteristics.

In this study, we present comprehensive optical characterization and spatial mode analysis of InGaN-based edge-emitting lasers realized on the thin-film platform. Under optical pumping conditions using a 393 nm nanosecond-pulsed laser, we demonstrate robust room-temperature lasing at a wavelength of 449.5 nm, characterized by a threshold excitation power density of 85 W/cm² and a high Q factor of 4200. To investigate the spatial mode distribution and optical confinement properties, scanning near-field optical microscopy (SNOM) is utilized in a configuration employing far-field excitation with near-field collection. Specifically, the devices are excited by a 405 nm continuous-wave laser incident in the far-field, while the resultant emission is collected through a fiber probe positioned in close proximity to the laser cavity surface. The experimentally obtained near-field emission profiles closely resemble the simulated electric field intensity distributions obtained from finite-element simulations, thus confirming the designed resonant mode patterns and waveguiding mechanisms.

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PC-Tue-P42* - Determination of quantum efficiency of InGaN-based light emitting diodes grown by plasma-assisted molecular beam epitaxy

2. Physics and characterization

Szymon Lach[1]
Mateusz Hajdel[1], Marcin Siekacz[1], Mikołaj Żak[1], Czesław Skierbiszerski[1], Grzegorz Muziol[1]
[1] Institute of High Pressure Physics PAS, Warsaw, Poland

Abstract text: InGaN-based light emitting diodes grown by plasma-assisted molecular beam epitaxy (PAMBE) are (in)famous for their low external quantum efficiency (EQE) compared to the similar devices grown using metalorganic vapor-phase epitaxy (MOVPE) method. The reported EQE of devices grown by PAMBE rarely exceed 1%[1]. In comparison, LEDs grown by MOVPE can reach up to 80% EQE [2]. Recently, we have modified the growth conditions in PAMBE, by significantly increasing the growth temperature. This led to considerable improvement in intensity of emitted light from the heterostructures. However, determination of EQE, requires careful consideration, since only a part of light emitted from the active region of LED is extracted from the device.
It this paper we study the limiting factors of light extraction efficiency (LEE). For this purpose, we created a Monte Carlo ray-tracing simulation of photon packets traveling inside InGaN-based LEDs. Two different base geometries were examined: a regular triangle and a square, as well as the height of the simulated devices. To avoid further complications during analysis, ray scattering and surface roughness of external surfaces were not simulated. As a result, the obtained LEE from simulation represents the lower boundary.
Our simulation showed higher light extraction efficiency for triangular-based devices, reaching approximately 25%, compared to the LEE of around 14% for square-based devices. Therefore for the experimental part we have chosen the triangular base geometry of the devices.
Two devices were grown by PAMBE. Devices differed mainly in the width of the quantum well, 25 nm for the device A and 3 nm for the device B, and in the growth temperature, which was higher (710°C) for device A compared to the device B (690 °C). Measurements of triangular-based InGaN light emitting diodes mounted in flip-chip configuration were conducted. We observed an external quantum efficiency as high as 32% for device A and 22% for device B. These values are uncommonly high for MBE-grown devices.

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PC-Tue-P43 - Misfit accommodation in a single atomic layer at a highly lattice-mismatched InN/GaN interface

2. Physics and characterization

Tomoki Nagase[1]
Kenta Chokawa[1], **Emi Kano**[1], Keisuke Fukuta[1], Kenji Shiraishi[1], Atsushi Oshiyama[1], Tsutomu Araki[2], Nobuyuki Ikarashi[1]
[1] Nagoya university, Nagoya, Japan
[2] Ritsumeikan university, Kusatsu, Japan

Abstract text: Semiconductor heterostructures control the fundamental properties of semiconductors and form the basis of various electronic and optical devices. Lattice mismatch, inevitable in heterostructures, generates misfit dislocations (MDs), hindering the synthesis of distinct material properties. Therefore, interfacial structures have been extensively studied. However, for the interfaces with large lattice mismatches, such as InN/GaN (0001) with an 11.1% mismatch, the structural characteristics and mismatch accommodation mechanisms remain unclear. [1]
Here, we report the atomic structure of the InN/GaN interface using atomic-resolution transmission electron microscopy (TEM) and large-scale first-principles calculations. Our findings show that atomic rearrangement in the InN single layer accommodates the lattice mismatch without MDs, suggesting a fundamentally different accommodation mechanism. We propose that the key factor in the interface structure is the flexibility of the group III – nitrogen bond network.
The InN/GaN structure was prepared using radio-frequency plasma-assisted molecular beam epitaxy. InN layers were grown on a (0001) GaN surface under a layer-by-layer growth condition. [2] High-angle annular dark field scanning TEM (HAADF-STEM) was used to directly observe the atomic positions of group III atoms at the interface along three orthogonal zone axes: <11-20>, <1-100>, and <0001>. First-principles calculations based on density functional theory (DFT) using our real-space scheme [3] were performed to investigate the atomic configurations. A slab model was used, consisting of three InN (0001) monolayers on three GaN (0001) monolayers. The lateral dimensions of the supercell were set to InN 9×9 and GaN 10×10 according to the InN/GaN lattice mismatch.
Our analysis revealed that a single InN atomic layer with structural modifications is sandwiched between wurtzite InN and GaN. The interfacial InN layer consists of three domains, eliminating the unstable stacking. Group III-N bond lengths deviate by ± 4-5 % and bond angles by 15 % at the interface. This flexibility is critical for the interfacial bonding network, allowing the 11.1% mismatch to be accommodated without MD formation.
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PC-Tue-P44 - Investigation of wide-bandgap semiconductor materials by optical defect spectroscopy and THz-TDS

2. Physics and characterization

Christian Röder[1]
Kuei-Shen Hsu[2], Joshua Hennig[3], Daniel Molter[3], Jan Beyer[2], Franziska C. Beyer[1], Johannes Heitmann[4]
[1] Fraunhofer Institute for Integrated Systems and Device Technology IISB, Schottkystr. 10, 91058 Erlangen, Germany
[2] TU Bergakademie Freiberg, Institute of Applied Physics, Leipziger Str. 23, 09599 Freiberg, Germany
[3] Fraunhofer Institute for Industrial Mathmatics ITWM, Fraunhofer-PLatz 1, 67663 Kaiserslautern, Germany
[4] Fraunhofer Institute for Integrated Systems and Device Technology IISB, Schottkystr. 10, 91058 Erlangen, Germany; TU Bergakademie Freiberg, Institute of Applied Physics, Leipziger Str. 23, 09599 Freiberg, Germany

Abstract text: Wide-bandgap semiconductor materials, such as Gallium Nitride (GaN), Silicon Carbide (SiC) or Aluminium Nitride (AlN), are crucial for high-power and high-frequency electronic devices, as well as optoelectronic applications, including light-emitting diodes (LEDs) and laser diodes, due to their superior physical properties. Since carrier density and mobility are important parameters that significantly influence the performance of semiconductor devices, spatially resolved measurements are of increasing interest for non-destructive testing and mapping.

The THz time-domain spectroscopy (THz-TDS) is a well-established technique which can probe the dielectric properties of materials in the THz region on the one hand. On the other hand, optical defect spectroscopic methods, such as micro-Raman scattering or photoluminescence spectroscopy (PL), provide insights into vibrational properties, crystal quality, and defect states. The combination of both optical defect spectroscopy and THz-TDS characterization facilitates a comprehensive analysis of wide-bandgap semiconductors.

In this study, the relationships between structural defects, carrier dynamics, and overall material performance are evaluated by correlating the vibrational, defect spectroscopic and electronic properties derived from the applied techniques. The results will be discussed in terms of semiconductor quality as well as electrical homogeneity and are complemented by electrical measurements (e.g., C-V). The integrated approach which is presented is essential for advancing the development of next-generation electronic and optoelectronic devices based on wide-bandgap semiconductor materials, ultimately leading to improved efficiency and functionality in various applications.

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PC-Tue-P45* - Microscopic Understanding, Engineering, and Utilization of Defect Behavior in Wide-Bandgap Semiconductors

2. Physics and characterization

Zhiming Shi[1]
Hang Zang[1], Ke Jiang[1], Xiaojuan Sun[1], Dabing Li[1]
[1] State Key Laboratory of Luminescence Science and Technology, Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP), Chinese Academy of Sciences, Changchun, Jilin, 130033, P. R. China

Abstract text: Defects are intrinsic structural features in semiconductor materials, and every significant advancement in semiconductor technology has been accompanied by an better understanding of defect behavior. Wide-/ultrawide-bandgap semiconductors, such as GaN, SiC, Ga_2O_3, BN, and diamond, have emerged as key materials following the dominance of Si- and GaAs-based technologies. These materials have enabled a wide range of applications in optoelectronics and micro/nanoelectronics. However, defects in these materials remain a critical limitation to device performance. Thus, a deeper understanding of defects and the ability to effectively engineer them are essential for further improving device functionality.

We initiates from fundamental physical properties—including structural characteristics, electronic properties, and localized phonon behavior—to reveal how defect structures (such as dislocations and point defects) influence optoelectronic performance. Furthermore, we propose defect engineering strategies and demonstrate defect-enabled performance enhancement through first-principles calculations. First, we demonstrated that the grain boundary can create robust diluted magnetic semiconductors in AlN. Moreover, we developed a localized band offset compensation strategy to lower carrier activation energy, the carrier density can be enhanced several magnitudes in AlGaN (*p*-type) and BN (*n*-type). Finally, we investigated the phonon-electron coupling and optical properties of point defects in the wide-gap III-nitrides. We theoretically addressed carrier injection asymmetry in LEDs via nitrogen-vacancy defects and designed single-photon color-centers based on cation vacancies.

With the gradual deepening of the understanding of defect behavior and the continuous advancement of defect engineering, defects will no longer only have a negative impact on materials. Rational defect engineering will also become a new approach to improving material properties.

PC-Tue-P46* - real time observation of stacking fault migration

2. Physics and characterization

Xifan Xu[1]
fangcheng wang[1], qi liu[1], tao wang[1], xinzheng li[1], ping wang[1], bo shen[1], xinqiang wang[1]
[1] peking university china

Abstract text: Stacking faults (SFs), disruptions in atomic plane sequence, are critical planar defects that have been studied for decades, yet they have never been observed to migrate—the most fundamental motion for other planar defects. Here, we report real-time atomic-scale observations of the migration of prismatic stacking faults (PSFs) using III-nitride semiconductors as representative systems, where PSFs, typical defects in wurtzite crystals, are inherently abundant. Based on atomic paths captured in real-time and further leveraging first-principles simulations, we quantitatively identify migration energy barriers, revealing that PSF migrates by transitioning into Ox-like and Crab-like phases, which act as steppingstones that significantly lower the migration energy barriers. These findings broaden the scope of defect physics and provide critical guidance for further optimizing semiconductor devices.

PC-Tue-P47 - AlN/GaN Heterostructures: A Nanosecond Pulsed I-V Study by Undergraduate Engineering Students for Extracting the Velocity–Field Dependence

2. Physics and characterization

Ernesto Momox[1]
Romina Nájera-Fuentes[1], Juan P Guerrero-Escudero[1]
[1] Tecnológico de Monterrey, Querétaro, Mexico

Abstract text: This work focuses on the experimental evaluation of AlN/GaN heterostructures using an optimized nanosecond pulsed I-V measurement setup. By employing a robust pulsed I-V technique, our approach minimizes self-heating, ensuring precise extraction of the velocity–electric field (v–F) characteristics that are critical for device simulation and design.

The AlN/GaN heterostructures investigated comprise a 2 nm GaN cap layer, a 1.5 nm AlN barrier, and a 500 nm undoped GaN layer grown on a Fe-doped semi-insulating GaN pseudo-substrate (MOCVD on (0001) sapphire), with a 0.5 µm GaN buffer layer to enhance epitaxial quality. Hall measurements reveal a well-defined two-dimensional electron gas (2DEG) with a sheet carrier density of approximately 8.2×10^{12} cm^{-2} and a room-temperature mobility of 520 $cm^2/V\cdot s$.

Experimental results show a maximum drift velocity of 3.2×10^7 cm/s at an electric field of roughly 120 kV/cm. Notably, a small region of negative differential mobility (NDM) is observed. The existence of NDM in GaN was theoretically predicted several years ago based on its unique electronic properties and hot electron effects. Our experimental observation of NDM not only confirms these early predictions but also highlights the complex interplay between hot electron dynamics and phonon interactions under high electric fields.

Furthermore, the obtained v–F data were carefully fitted to a well-established two-dimensional mobility model, which provides essential parameters for high-field device simulations using tools such as Sentaurus TCAD. This model fitting offers a robust framework for bridging experimental insights and numerical simulations in the realm of nitride semiconductor devices.

Overall, the integration of advanced nanosecond pulsed I-V measurements, thorough sample characterization, and precise model fitting deepens our understanding of electron transport in AlN/GaN heterostructures and paves the way for further improvements in the simulation and design of high-performance nitride semiconductor devices.

PC-Tue-P48* - The characterization of self-built electric field via the Urbach tail

2. Physics and characterization

Sha Han[1]
Ke Xu[1]
[1] The Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, Suzhou, China

Abstract text: Contrary to the traditional characterization method via the Franz-Keldysh oscillations (FKO) which is a weak signal, here we propose to obtain the self-built electric field via the Urbach tail part which is direct and versatile. According to the Franz-Keldysh theory, FKO's period is related to F which only applies for the uniform and wide electric field. To validate our method, one important step is to reveal the inner connection between the broadening factor γ and the width L of the electric field. The Urbach tail becomes more and more smooth via increasing γ or L and the final absorption α is same when taking a large enough value for γ and L.Thus the simulation for three factors (γ, F and L) is simplified to the simulation for F only. What's more, we tried to fit the electric field F for two Si-doped GaN single crystals with different doping levels and the results are comparable to the results via other established methods. The good coincidence between our method and other methods prove the rationality of our methods. By analyzing the root mean square errors (RMSE) between the experimental and fitted α, our method is more superior.

PC-Tue-P49 - Multi-fields Coupling in Nitride Semiconductors and Stress Imaging Systems

2. Physics and characterization

Junyi Zhai[1]

[1] Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, China

Abstract text: Multi functional micro/nano devices and systems have important applications in intelligent electronic products, such as healthcare, human-machine interfaces, infrastructure monitoring, and security. Piezotronics provides a new method to significantly improve/regulate the electronic and optoelectronic performance of semiconductor devices. The principle of piezotronics is to regulate the generation, transmission, separation, and/or recombination of charge carriers at heterojunctions/interfaces by adjusting the piezoelectric potential generated by externally applied strains. This speech summarizes the design and principles of prototype devices in (1) piezotronics, piezo-phototronics, and flexotronics, (2) novel all optical mechanical sensors based on piezo-phototronics GaN multi-wells nanopillars and real-time high-resolution stress imaging of live cell forces.

PC-Tue-P50 - THERMAL CONDUCTIVITY OF WURTZITE ScAlN: EFFECT OF LAYER THICKNESS

2. Physics and characterization

Dat Q. Tran[1]
Agne Žukauskaitė[2], Stephan Barth[2], Hagen Bartzsch[2], Vanya Darakchieva[3], Plamen P. Paskov[1]
[1] Department of Physics, Chemistry, Biology, Linköping University, 581 83 Linköping, Sweden
[2] Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology, 01277 Dresden, Germany
[3] NanoLund and Solid State Physics, Lund University, 22100 Lund, Sweden

Abstract text: Owing to its large piezo- and spontaneous polarization wurtzite (*wz*) ScAlN is a promising material for high-frequency electronic devices, such as ScAlN/GaN high electron mobility transistors [1]. Effective thermal management is essential to mitigate self-heating, making accurate knowledge of the thermal conductivity of the device materials crucial.

In this work, we report the thermal conductivity (ThC) of *wz*-$Sc_xAl_{1-x}N$ layers with Sc composition up to $x = 0.41$ grown by magnetron sputtering epitaxy on Si(111) and sapphire substrates. The measurements are performed by transient thermoreflectance technique within a temperature range of 80–400 K. Furthermore, we investigate the boundary effects on thermal conductivity and heat transport across the layer/substrate interface. To achieve this, the experimental data are analyzed using a modified Callaway model, which accounts for all relevant phonon scattering processes [2].

The experimental data and calculations for layers with different compositions and thicknesses (80–2000 nm) reveal a significant impact of the phonon-layer-boundary and phonon-grain-boundary scattering on the ThC. At low temperatures, ThC is primarily limited by layer-boundary scattering, while grain-boundary scattering becomes dominant above room temperature. Both effects diminish as layer thickness increases.

Furthermore, we investigated the temperature dependence of the thermal boundary resistance (TBR) across the ScAlN/Si(111) interface and found that it saturates at temperatures above 200 K at a remarkably low value. This result indicates a diffusive phonon transport mode across the interface, which is consistent with our calculations using non-equilibrium Landauer approach and employing exact phonon density of state [3].

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PC-Tue-P51 - Ultra-low Sheet Resistance of ScAlN/GaN HEMTs

2. Physics and characterization
Jiangnan Liu[1]
Zetian Mi[1]
[1] University of Michigan, Ann Arbor

Abstract text: One of the pivotal factors affecting HEMT performance is the sheet carrier resistance (R_{sh}), which is related to the sheet carrier density (n_s) and the carrier mobility (μ). Scandium aluminum nitride (ScAlN) has emerged to show enhanced piezoelectricity and spontaneous polarization, attracting significant attention to be explored as a novel barrier material in HEMT. ScAlN can also be nearly lattice matched to GaN so that the critical thickness limitation seen in the AlN/GaN structure is eliminated while the interface can be well controlled with low roughness and minimal defects. These properties are in favor of high mobility for HEMTs. Moreover, the conduction band offset between ScAlN and GaN exceeds 2 eV, larger than that between AlN and GaN (~1.5 eV),[3] which contributes to an improved carrier concentration, paving the way for reduced sheet resistance at higher power and frequency operations.

In this study, we have grown ScAlN/GaN-based HEMT structures using plasma-assisted molecular beam epitaxy (PA-MBE). A series of samples with varying $Sc_{0.15}Al_{0.85}N$ barrier thickness ranging from 0 nm to 24 nm was grown on GaN with a thin (2 nm) layer of AlN inserted to mitigate alloy disorder scattering. The structure is illustrated in Fig. 1. Hall effect measurement has revealed that using ScAlN as the barrier can drastically improve the carrier density and increase the ScAlN thickness can further enhanced the 2DEG density, achieving a peak concentration of 7.8×10^{13} cm^{-2} and reducing the R_{sh} to a record low of 95.5 Ω/□ when incorporating 15 nm ScAlN in the barrier layer. Temperature-dependent Hall effect measurements further showed robust transport properties, with mobility exceeding 4000 $cm^2/V \cdot s$ and R_{sh} evaluating to as low as 33.3 Ω/□ at 10 K.

In conclusion, incorporating ScAlN as the barrier material in GaN HEMTs enables record-high 2DEG carrier concentrations and low sheet resistance at room temperature, highlighting significant potential for improved performance in power and RF electronics. The advancements in epitaxial growth and precise control over barrier properties allow for further tailoring of device parameters, paving the way for next-generation electronic devices.

PC-Tue-P52* - Determination of electronic structure parameters from spectroscopic ellipsometry and GW calculations: A case study on non-degenerate ScN

2. Physics and characterization

Jona Grümbel[1]
Yuichi Oshima[2], Hazem Abu-Farsakh[3], Abdallah Hamoudeh Qteish[4], Rüdiger Goldhahn[1], Martin Feneberg[1]
[1] Otto-von-Guericke-Universität, Institut für Physik, Magdeburg, Germany
[2] Research Center for Electronic and Optical Materials, National Institute for Materials Science, Tsukuba, Japan
[3] Department of General Sciences, Prince Sultan University, Riyadh, Saudi Arabia
[4] Department of Physics, Yarmouk University, Irbid, Jordan

Abstract text: We combine a fundamental discussion of various models used to describe the dielectric function of semiconductors in the NIR-UV spectral range with the evaluation of electronic structure parameters in ScN. ScN is an indirect bandgap semiconductor with a bandgap comparable to Si and a lowest direct bandgap in the VIS spectral range, typically exhibiting unintentional free carrier concentrations beyond the degeneracy limit. To complement or improve state-of-the-art III-N based (opto-)electronic devices like LEDs or high-electron-mobility transistors (HEMTs), ScN oers unique possibilities e.g. by alloying with AlN for enhanced piezoelectricity or as (transparent conductive) buffer layer for lattice-matched GaN growth. We first present spectroscopic ellipsometry results of 8 high quality, non-degenerate, quasi-bulk ScN epilayers, where our analysis yields precise values of the direct X- and Γ-point critical point transition energies with low variance across all samples and the dielectric background constant ε_∞. We determine E_Γ = (3.853 ± 0.006)eV, $E\Gamma'$ = (5.21 ± 0.02)eV, and ε_∞ = 8.40 ± 0.1, where we do not observe any discrete exciton states. The lowest direct absorption edge is expected to be influenced by free carriers even in the non-degenerate regime, so we use band-filling and band-gap renormalization equations to calculate the intrinsic lowest direct band gap, where we obtain $E_{X,0}$ = (2.182 ± 0.004)eV. Various methods for the determination of bandgaps (Elliott's and Aspnes' model as well as the widely misused Tauc-plot method) and for the dispersion of the refractive index (Shokhovets' and Sellmeier model) are discussed in detail. Our results suggest that the samples well represent the optical properties of pure bulk-ScN and hence our determined parameters are excellently suited for calibration of theoretical calculations performed on ScN. So at a second stage, we conduct precise calculations including quasi-particle correction within the G_0W_0 approach on top of hybrid-functional (HSE06) density-functional-calculations to derive the band structure of ScN. Thereof, the dielectric function is obtained by solving the Bethe-Salpeter-equation, which includes excitonic effects, and a detailed comparison to the experimental data is presented.

PC-Tue-P53* - Optical Detection of Sliding Ferroelectric Switching in hBN with a WSe2 Monolayer

2. Physics and characterization

Sébastien Roux[1]
J. Fraunié[1], B. Lassagne[1], C. Robert[1]
[1] Université de Toulouse, INSA-CNRS-UPS, LPCNO, 135 Av. Rangueil, 31077 Toulouse, France

Abstract text: Thanks to its 6.25 eV band gap and honeycomb lattice, hexagonal Boron Nitride (hBN) has been widely used in 2D material heterostructures as an atomically flat insulating substrate or as a dielectric barrier. More than just a capping material, Boron Nitride layers can be functionalized in many ways, for example by adding external defects to the lattice or by playing with the structure (twist angle, stacking sequence), which opened the route to its integration into complex van der Waals heterostructures combining hybrid properties.

In particular, when two hBN flakes are stacked with a near-zero twist angle, a spontaneous out-of-plane electric polarization occurs at the interface. This polarization is characterized by large reconstructed domains with alternating direction [1-4], and can be switched by applying an out-of-plane electric field. A process driven by the in-plane sliding of one BN layer with respect to the other. In this work, we investigate the coupling of such a ferroelectric hBN interface with a 2D semiconductor, a WSe_2 monolayer. First, the influence of the spontaneous polarization of hBN on the charge density of WSe_2 is quantified. Finally, we demonstrate that WSe_2 photoluminescence can be used to detect the sliding process and its associated hysteresis. This offers a new approach to probe this emerging class of interfacial ferroelectricity [5–6].

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OD-Tue-P1* - Post-wet-etching of Ni/Au ohmic contact to enhance the light extraction efficiency of AlGaN-based DUV LEDs

3. Optical devices

Jianchang Yan[1]
Linhao Wang[2], Bing Wang[1], Naixin Liu[1], Yonghui Zhang[2], Jinmin Li[3]
[1] Research and Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China
[2] School of Electronics and Information Engineering, Hebei University of Technology, Tianjin, China
[3] Advanced Ultraviolet Optoelectronics Co., Ltd., Shanxi, China

Abstract text: AlGaN-based deep-ultraviolet light-emitting diodes (DUV LEDs) provide advantages including long lifetime, high energy efficiency, and easy integration with control system over traditional mercury lamps. Nevertheless, the wall-plug efficiency (WPE) of DUV LEDs remains below 10%, which hinders their explosive application. The limited WPE mainly arises from the low light extraction efficiency (LEE), which is associated with the severe total internal reflection, especially for the significant proportion of TM-polarized light, and the optical absorptivity of photons by the p-type epitaxial contact layer and metal electrodes. Ni/Au is widely used as an anode for commercial DUV LEDs due to its low ohmic contact resistance, cost-effectiveness, and excellent reliability. However, its typically exhibits only 30% reflectivity, making the highly reflective metal pads unable to well function.

In this work, we propose a post-wet-etching of the Ni/Au ohmic contact in a Au corrosive liquid to improve its optical transmittance and the LEE of DUV LEDs. The Au corrosive liquid is a sulfonitric mixed acid mainly composed of 4% KI and 4.5% I_2. Experimental results show that the optical transmittance of the Ni/Au electrode can be improved from 35.2% to 42.68% after 5-min wet-etching. The optical power and the WPE of the proposed device are enhanced by 10.24% and 9.89% respectively at an injection current of 100 mA compared to the untreated counterpart (Devie R). The FDTD simulation reveals that the TE-polarized light is more sensitive to the post-wet-etching time in increasing the LEE than the TM-polarized light. This is because more TE-polarized light can be reflected into escape cones. Moreover, the post-wet-etching of Ni/Au leads to a slight increase of 0.30 V in forward voltage, but the treatment hardly affects the device's stability after a 1000-h aging test. Therefore, our proposed method not only can improve the LEE at the expense of a small voltage increase, but also is fully compatible with the mass production of DUV LEDs.

OD-Tue-P2* - Room temperature electroluminescence of Pr-implanted GaN p-n junction diode

3. Optical devices

Shin Ito[1]
Shin-ichiro Sato[2], Michal Boćkowski[3], Manato Deki[4], Hirotaka Watanabe[5], Shugo Nitta[6], Maki Kushimoto[1], Atsushi Tanaka[5], Ken-ichi Yoshida[7], Hideki Minagawa[7], Yoshio Honda[5], Hiroshi Amano[5]
[1] Graduate School of Engineering, Nagoya University, Nagoya, Aichi, Japan
[2] National Institutes for Quantum Science and Technology, Takasaki, Gunma, Japan.
[3] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland.
[4] Deep Tech Serial Innovation Center, Nagoya University, Nagoya, Aichi, Japan.
[5] Institute of Materials and Systems for Sustainability, Nagoya, Aichi, Japan.
[6] Innovation Center for Semiconductor and Digital Future, Mie University, Tsu, Mie, Japan.
[7] Ion Technology Center Co.,Ltd, Hirakata, Osaka, Japan.

Abstract text: The single-photon source (SPS), a quantum device that can generate single photons on demand, is crucial for the development of quantum communication technologies. Isolated rare-earth (RE) ions in semiconductors, whose luminescence transition in the 4f-shell is inherently single photon emission, are a promising candidate for SPS operating at room temperature (RT) because of their stable photon emission with a narrow linewidth even at RT and their potential of electric control (*i.e.* electroluminescence: EL). In particular, GaN is the suitable host since RE ions do not show significant thermal quenching at RT due to its large bandgap (3.4 eV). Ion implantation technique is used to fabricate electrically driven RE-SPS, ensuring precise RE ion positioning and quantity control. However, limited studies exist on EL characteristics of RE-doped GaN diodes fabricated by ion implantation.

Here we show that Pr-doped GaN devices were successfully fabricated through crystal growth, ion implantation, annealing, regrowth, and device fabrication. A n^--GaN layer was grown on a GaN substrate, followed by Pr ion implantation at 700 keV with a dose of 1×10^{14} cm^{-2}. Ultra-high-pressure annealing was performed at 1400 °C for 10 min under 1 GPa N_2, after which a p-GaN layer was regrown to form a p-n diode. The I-V measurements showed rectifying behavior. However, irradiation-induced defects at the p-n junction generated by ion implantation caused an increase in series resistance. The EL measurements revealed that a sharp emission peak appeared at 652 nm, which matched the PL emission of Pr^{3+} in GaN [1]. This fact indicates that the observed EL also originated from the Pr-related transition. Additionally, the I-L characteristics showed a positive correlation between the sharp peak intensity and injection current. These results indicate that the EL in the Pr-doped GaN device is caused by the energy transfer from carrier recombination [2].

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OD-Tue-P3* - Highly Reflective and Conductive a New Ni/Al/Au p-electrode for 292 nm UVB LED on C-plane Sapphire

3. Optical devices

Hamida Zia[1]
Amina Yasin[2], Fujimoto Kohei[3], Nagata Yuya[3], Yaguchi Hiroyuki[3], Muhammad Ajmal Khan[2], Hirayama Hideki[2]
[1] RIKEN Cluster for Pioneering Research (CPR), 2-1 Hirosawa, Wako, Saitama, 351-0198 Japan.
[2] RIKEN Cluster for Pioneering Research (CPR), 2-1 Hirosawa, Wako, Saitama, 351-0198 Japan
[3] Saitama University, Saitama 338-8570, Japan

Abstract text: AlGaN-based ultraviolet-B light-emitting diodes (UVB-LEDs) have gained attention due to their compact size, energy efficiency, and long lifespan, making them a promising alternative to conventional mercury-based UV lamps for applications in phototherapy, sterilization, water purification, agriculture, environmental monitoring, and industrial curing [1-3]. However, their external efficiency (EQE) remains significantly lower than that of blue LEDs, primarily due to their low light-extraction efficiency (LEE). The reason for low LEE in these devices is mainly attributed to factors such as high internal reflection due to the high refractive index of AlGaN and absorption losses in the p-GaN layer. Our group previously demonstrated that LEE could be significantly improved by introducing a transparent contact layer and a highly reflective Ni/Al p-electrode [2,3]; however, this approach suffered from poor current-voltage (I-V) characteristics due to inadequate contact between the p-electrode and p-AlGaN. To address this issue, herein, we developed 291-292 nm UVB LEDs with high-LEE by incorporating a new combination of Ni/Al/Au p-electrode with optimized thickness. In this work, we optimized the new type of Ni (10 nm)/Al(20 nm)/Au(100 nm) p-electrode for AlGaN UVB LEDs. Consequently, we conducted a comparative study on the same wafer under continuous-wave (CW) operation using a conventional Ni (20nm)/Au(100nm) p-electrode and a new type of Ni(10nm)/Al(20nm)/Au (100nm) p-electrode. The Ni/Al/Au configuration demonstrated 35% higher reflectance and improved electrical conductivity, as observed in the I-V characteristics. This enhancement is attributed to the combined effect of highly reflective Ni (10 nm), Al (20 nm), and Au (100 nm) layers, which significantly improve both optical and electrical properties. These findings offer valuable insights for the advancement of next-generation high-efficiency optoelectronic devices.

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OD-Tue-P4* - 240 nm AlGaN-Based Deep Ultraviolet Micro-LEDs: Carrier Transport, Sidewall Engineering, and Nanorod Optimization

3. Optical devices

Shunpeng Lu[1]
Ke Jiang[1], Jianwei Ben[1], Shanli Zhang[1], Xiaojuan Sun[1], Dabing Li[1]
[1] State Key Laboratory of Luminescence Science and Technology, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

Abstract text: 240 nm AlGaN-based micro-LEDs have high potential for non-light-of-sight optical communication, human harmless sterilization, and mask-less photolithography. However, the external quantum efficiency (EQE) is limited by the current crowding effect, edge effect and low light extraction efficiency (LEE) with Al component increasing. Therefore, we systematically studied those factors to obtain a high efficiency. Firstly, the uniformity of carrier distribution and LEE are simultaneously enhanced by employing a strategy that combines elongated tilted sidewalls with sidewall Al reflectors. It is revealed that the peak optical output power increases by 81.83% with the micro-LED size shrinking from 50.0 μm to 25.0 μm. Thereinto, the LEE increases by 26.21% and the LEE enhancement mainly comes from the sidewall light extraction. Most notably, TM mode light intensifies faster as the size shrinks due to the tilted mesa side-wall and Al reflector design. Secondly, we investigated the enhancement of light efficiency in different devices through KOH treatment by restoring sidewall damage. The peak light output power density increases from 2.12 W/cm^2 to 4.01 W/cm^2, representing an 89.2% increase. Thirdly, we presented a novel strategy to enhance LEE by employing gold thin-film annealing and dry-etching techniques to fabricate disordered p-GaN/p-AlGaN hybrid nanorod arrays. 3D finite-difference time-domain simulations predict a 79% increase in LEE for TM and a 187% improvement for TE. Experimentally, we observe a 140% enhancement in peak light output power (LOP), a 148% boost in external quantum efficiency (EQE), and a 146% increase in wall-plug efficiency (WPE) at 1 mA compared to planar designs. The efficiency enhancement of Micro-LEDs is anticipated to facilitate the development of DUV Micro-LEDs in maskless lithography and high-capacity DUV non-line of sight communication.

OD-Tue-P5* - Wafer-scale vertical injection AlGaN-based DUV-LEDs

3. Optical devices

Jiaming Wang[1]
Chen Ji[1], Jing Lang[1], Fujun Xu[1], Lisheng Zhang[2], Xiangning Kang[1], Zhixin Qin[1], Weikun Ge[1], Bo Shen[1]
[1] State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing , China
[2] Beijing SinoGaN Semiconductor Technology Co., Ltd., Beijing, China

Abstract text: AlGaN-based deep-ultraviolet light-emitting diodes (DUV-LEDs) have attracted much attention in the field of public and personal sterilization, owing to their advantages of environment friendly, long lifetime and portability. Benefiting from the improvement of crystalline quality and the optimization of device structure, great progress in device performance has been made in the past decade, where the peak wall-plug efficiency and external quantum efficiency reach 15.3% and 20.3% for 275 nm DUV-LEDs, respectively. There is, however, still a considerable gap from InGaN-based visible LEDs. In particular, DUV-LEDs are suffering from the low light extraction efficiency with a typical value of single-digit percent (6–8%) if without addition improvement features. One of the key issues is the narrow escape cone of DUV light emitted from the active region, attributed to the total internal reflection (TIR) at the AlN/sapphire and sapphire/air interfaces.

Vertical injection configuration is hence considered as a thorough solution for DUV-LEDs with preferable performance, where the substrate is removed to fundamentally overcome the TIR issue. Herein, we propose a ground-breaking roadmap of DUV-LEDs based on GaN templates instead of conventionally adopted AlN. The primary concern of the tensile strain for Al-rich AlGaN on GaN is addressed via an innovative decoupling strategy, making the device structure decoupled from the underlying GaN templates. Moreover, the strategy provides a protection cushion against the stress mutation during the removal of substrates. As such, 2 and 4 inch wafers can be obtained without surface cracks, even after the removal of the sapphire substrates by laser lift-off. Wafer-scale fabrication of 280 nm vertical injection DUV-LEDs is eventually demonstrated, where a light output power of 65.2 mW is achieved at a current of 200 mA. It is the first time that the 2 and 4 inch substrates can be easily and efficiently removed for DUV emitters, greatly driving it into a new era featuring high performance and scalability.

OD-Tue-P6* - New localized landscape Model for Absorption and Emission Spectra with Polarization Ratio in AlGaN-Based UV LEDs with Alloy Fluctuation.

3. Optical devices

Ping-Jie Zhuang[1]
Marcel Filoche[2], **Yuh-Renn Wu**[1]
[1] Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei 106319, Taiwan
[2] Institut Langevin, ESPCI Paris, PSL University, CNRS, 75005 Paris, France

Abstract text: Traditionally, studying the emission spectrum, especially TE/TM polarization, is time-consuming because it requires solving the k·p model along with a self-consistent Poisson, drift-diffusion, and Schrödinger k·p solver. This complexity hinders investigations of how alloy fluctuations under strain affect emission and absorption. The localization landscape (LL) model [1] offers an effective quantum potential that lets the drift-diffusion equation include quantum effects for better carrier density predictions. However, modeling the emission spectrum remains challenging even with LL. In 2023, a new LL-based approach was proposed to calculate both the emission and absorption spectra without solving the eigenvalue problem.

Using the Wigner–Weyl formalism in the LL model—which efficiently represents electron and hole eigenstates in disordered materials [2] demonstrated that coupling the LL model with Wigner–Weyl analysis provides a more accurate description of the absorption tail and Urbach energy in AlGaN alloys by coupling quantum localization effects. Inspired by this approach, we apply the LL model to 3D simulations of AlGaN structures, considering both strain-induced band mixing and random alloy fluctuations. We then compare the absorption and emission spectra from the LL model with those calculated using the k·p method [3] (not self-consistently coupled with Poisson DD—3D self-consistency would require immense resources). Our results show that the LL model reproduces similar emission trends while being more time-efficient than the k·p method.

Our simulations show that the pGaN layer, graded composition, and alloy fluctuations alter the average absorption spectrum. The Wigner–Weyl LL method improves efficiency and reveals how alloy disorder affects carrier localization, supporting LL-based emission modeling for LED analysis. Moreover, for QWs with >60% Al ($\lambda < 250$ nm), compressive strain induces a band switch between the $|Z\rangle$ and $|X \pm iY\rangle$ states, influencing TM/TE emission. Under these conditions, the enhanced LL model predicts the emission spectrum much more quickly, providing advantages for optimizing high-Al AlGaN LED performance.

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OD-Tue-P7* - Simulation of (Al,Ga)N-based UV LEDs including effects from disorder

3. Optical devices

Michael O'Donovan[1]
Robert Finn[2], Patricio Farrell[1], Timo Streckenbach[1], Julien Moatti[3], Thomas Koprucki[1], Stefan Schulz[2]
[1] WIAS Berlin, Germany
[2] Tyndall National Institute, Cork, Ireland
[3] Bordeaux INP, France

Abstract text: Due to its wide tunable direct bandgap, the semiconductor alloy aluminium gallium nitride (Al,Ga)N is of particular interest for light-emitting applications operating in the UV part of the electromagnetic spectrum [1]. Light emitting diodes operating at short wavelengths (<280 nm) suffer from poor quantum efficiency [1]. To guide LED design with improved efficiencies, simulation techniques capturing the relevant physics are an important tool.

In (Al,Ga)N alloys, treatment of – in particular – the valence states requires careful attention. Alloy disorder leads to carrier localization which can modify the density of states, and cause percolation currents in a device [2]. Additionally, states can be comprised of bands that facilitate emission of transverse electric (TE) or transverse magnetic (TM) polarized photons. The relative contribution of each depends on (among others) the alloy composition, heterostructure properties and carrier density. Using an atomistic tight binding (TB) model we investigate the impact of these factors on (Al,Ga)N quantum wells (QWs) with 48% and 75% AlN composition [3]. Results indicate that wider wells allow for better carrier confinement and a higher fraction of TE emission due to built-in polarization fields.

To capture the impact of alloy disorder and band mixing effects on carrier transport properties, we have developed a multiscale drift-diffusion framework which builds on results from TB [4]. Quantum corrections are included via localization landscape theory [5]. The framework accounts for alloy disorder and band mixing effects through a hybrid single band model. The electronic structure of the model was benchmarked against TB.

Using this advanced framework, device characteristics of a UV-C emitting LED structure containing multiple $Al_{0.75}Ga_{0.25}N$ QWs and an AlN electron blocking layer embedded in (Al,Ga)N barriers is studied using the drift-diffusion software ddfermi [6]. Particular attention is paid to understanding the current injection efficiency and radiative recombination efficiency.

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OD-Tue-P8 - Thermal stability deterioration in UVC LEDs

3. Optical devices
Grigory Onushkin[1]
Willem van Driel[1]
[1] Signify, Research, Eindhoven, The Netherlands

Abstract text: Recent progress in AlGaN-based UVC LED epitaxial growth, chip and package manufacturing enabled substantial improvements in performance and reliability of manufactured UVC LEDs offered to the market. Maturity levels of these AlGaN-based semiconductor technologies are still lagging in comparison with InGaN-based LEDs, emitting in the visible range. As a result, UVC LEDs are still relatively inefficient and significantly more expensive to compete equally with conventional mercury-based UVC lamps on a source level. One of the directions is to realize a cost-competitive disinfection system with optimized design, incorporating integrated UVC-LED based light source and utilizing key benefits of UVC LEDs, including expected long-term robustness. Such optimized design requires a detailed knowledge on UVC LED performance at various operating conditions and their stability over time.

Temperature stability of UVC flux plays essential role for UVC LEDs, due to their low efficiency and relatively high operating junction temperatures in applications. Various commercial UVC LEDs show significant diversity in flux thermal stability trends, e.g. relative flux between 80°C and 25°C (Hot-Cold (80/25) found to vary from 65% and up to 120%, while majority of measured LEDs are typically in the range between 80% and 90%. Moreover, some UVC LEDs show significant deterioration in the temperature dependency of the radiation power (up to additional 15% drop in Hot-Cold (80/25) values) after long-term (5~10 thousand hours) operation. Such significant variation and drift in thermal stability over time could result in either underperforming and dissatisfactory disinfection devises or more expensive UVC LED-based systems, which are over-designed in order to overcome observed variations in UVC LED performance at different application operating conditions and over time.

It will be essential for successful and sustainable LEDification of UV applications to address such essential topics within standardization and technical communities as a direction of future developments of the UV LED technology.

OD-Tue-P9 - Investigation of graded composition p-AlGaN for improved 330 nm ultraviolet light emitting diode performance

3. Optical devices

Peter Milner[1]
Vitaly Z Zubialevich[2], Sandeep M Singh[1], Pietro Pampili[2], Brian Corbett[2], **Peter J Parbrook**[1]
[1] Tyndall National Institute, Cork, Ireland and School of Electrical and Electronic Engineering, Univeristy College Cork, Cork, Ireland
[2] Tyndall National Institute, Cork, Ireland

Abstract text: Distributed polarisation doping (DPD), a technique in which the built-in polarisation fields in III-Nitrides are exploited to produce a 3D carrier gas, has enabled improved hole concentrations in AlGaN films compared to conventional impurity doping. However, the optimum mix of impurity doping with DPD-AlGaN is not fully understood and may be composition-dependent. In this work, three LED structures with varied *p*-doped regions only were grown by metalorganic chemical vapour deposition. The *p*-region in the first ('co-doped') LED consists of a 50 nm DPD-$Al_xGa_{1-x}N$:Mg layer (x = 0.35-0.00). A 'polarisation doped' LED, is compositionally identical to the first LED, but no Mg precursor was flowed. The *p*-region in a reference LED consisted of a uniform composition 50 nm Mg-doped $Al_{0.18}Ga_{0.82}N$. All LEDs were topped with a 10 nm p-GaN contact layer. Standard fabrication processing was performed to realise 100 μm diameter mesas, with Pd *p*-contacts.

Room temperature characterisation showed the co-doped LED as having the strongest electroluminescence intensity (ELI), followed by the reference, and the polarisation doped LED having the lowest. However, without Mg doping, a near-UV luminescence (NUVL) band was eliminated from the spectrum, while present in both Mg-doped LEDs. Numerical simulations revealed deleterious effects of the absence of Mg in the EBL on both electron overflow and hole injection, supporting the trend of experimental results. Meanwhile, grading of the *p*-AlGaN improves hole injection through a lessened valence band offset at the EBL.

Devices were further packaged for temperature-dependent measurements in a cryostat which showed increasing ELI with reduced temperature, largely owing to increased internal quantum efficiencies. Both LEDs with DPD-AlGaN showed a steady dependence on temperature, while the reference LED had a complex progression, highlighting the thermal dependence of the hole concentration. The voltage of the polarisation doped LED at 5 mA as a function of temperature also revealed the independence of DPD, as the voltage remained constant down to 12 K.

Temperature-dependent Hall effect measurements were carried out on three samples with corresponding doping approaches. These results indicate an improved hole concentration with both DPD and Mg is partly the cause of the improved performance in the corresponding LED.

OD-Tue-P10 - Enhanced performance of AlGaN-based DUV LEDs through Hole Injection Efficiency Promotion Enabled by Polarization Engineering

3. Optical devices
Yang Liu[1]
Hongchang Tao[1], Shengrui Xu[1], Tao Zhang[1], Jincheng Zhang[1], Yue Hao[1]
[1] State Key Laboratory of Wide-Bandgap Semiconductor Devices and Integrated Technology, Xidian University, Xi'an 710071, China

Abstract text: AlGaN-based deep ultraviolet light-emitting diodes (DUV LEDs) has demonstrated significant application potential in sterilization, communication, water purification. However, the further commercialization of DUV LEDs remains constrained by their relatively low external quantum efficiency (EQE), primarily attributed to the significantly lower hole mobility compared to electrons. This disparity impedes hole transport across the electron blocking layer (EBL), thereby reducing hole injection efficiency into the multiple quantum wells (MQWs) region and thus degrading the device performance [1], [2], [3]. To address this challenge, this study proposes a novel approach to enhance hole transport efficiency through polarization-induced electric field acceleration.

In this study, APSYS software was utilized to simulate the DUV LEDs. The device structure was displayed schematically in Fig. 1(a). The conventional DUV LEDs structure was denoted as Device A. To enhance the hole injection efficiency, two LED structures were investigated. 1) A single-gradient structure (Device B) featuring Ga-polar Al composition grading from 0.56 to 0.47 in the p-type insertion layer; 2) A dual-gradient structure (Device C) incorporating additional Al composition grading from 0.57 to 0.60 in the last quantum barrier layer along the Ga-polar direction. As shown in Fig. 1(d)-(f). Device C exhibit the highest light output power with 38.6 mW, while Device B shows 29.0 mW, and Device A possess the lowest LOP at 300 mA. Furthermore, the WPE curve also demonstrates the enhanced performance of the gradient structure for Devices B and C, which can be attributed to the promoted hole injection efficiency for these devices. The hole concentration in Fig. 2 demonstrates the higher hole concentration through Al-gradient structure. Fig. 1(f) also displays the EL spectra, Devices B and C shows significantly higher peak wavelength intensity. This work establishes that Al composition-graded structures effectively modulate polarization fields to enhance hole injection, providing critical theoretical guidance for device optimization through band engineering strategies.

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OD-Tue-P11 - Enhancement of Light Extraction of Deep Ultraviolet Light Emitting Diodes

3. Optical devices

Tien-Yu Wang[1]
Wei-Chih Lai[1], Syuan-Yu Sie[1], Sheng-Po Chang[2], Cheng-Huang Kuo[3], Jinn-Kong Sheu[1], Jong-Shing Bow[4], Yun-Chorng Chang[5]
[1] Department of Photonics, National Cheng Kung University, Tainan 70101, Taiwan
[2] Department of Microelectronics Engineering, National Kaohsiung University of Science and Technology, Kaohsiung 81157, Taiwan
[3] Institute of Lighting and Energy Photonics, College of Photonics, National Yang-Ming Chiao Tung University, Tainan 71150, Taiwan
[4] Integrated Service Technology Inc., Hsinchu 30078, Taiwan
[5] Research Center for Applied Sciences, Academia Sinica, Taipei 11529, Taiwan

Abstract text: The light extraction of deep ultraviolet light emitting diodes (DUV LEDs) is studied in this report. By the thermal oxidation process, the refractive indexes of the sidewalls of DUV LEDs are modified. The oxidized sidewalls possess lower refractive indexes, which are beneficial for light extraction. Therefore, the DUV LEDs with the oxidized side wall show improved light emitting intensity in the lateral emission. The output powers of DUV LEDs are increased by the enhanced light extraction, and the enhancement of output power ranges from 20 to 27% by varying the thicknesses of oxidation layers.

OD-Tue-P12 * - Efficiency of Carrier Injection to InGaN Multiquantum Wells

3. Optical devices
Agata Bojarska-Cieślińska[1]
Łucja Marona[1], Szymon Grzanka[1], Ewa Grzanka[1], Piotr Perlin[1]
[1] Institue of High Pressure Physics PAS

Abstract text: The performance of InGaN-based laser diodes (LDs) and light-emitting diodes (LEDs) is strongly influenced by carrier injection efficiency into multiple quantum wells (MQWs). This study investigates the impact of quantum barrier thickness, quantum well (QW) position relative to p- and n-type layers, and indium composition on carrier transport and recombination dynamics. Three distinct sample sets were fabricated using Metal-Organic Vapor Phase Epitaxy (MOVPE): (A) varying quantum barrier thickness, (B) two QWs with different indium compositions and position, and (C) two QWs with a varying indium content of the shallower QW. The samples were characterized using electroluminescence (EL), cathodoluminescence (CL), high-resolution X-ray diffraction (HRXRD), and nextnano simulations.

Our results reveal that the quantum barrier thickness plays a crucial role in hole transport. While a 5 nm barrier allows for uniform hole distribution across both QWs, increasing the barrier thickness to 20 nm leads to a significant reduction in hole population in the deeper QW, effectively converting the system into a single QW arrangement. The effect of indium composition was also investigated: a small (≤2%) difference results in uniform emission, whereas a larger difference (>2%) concentrates recombination in the deeper well, regardless of its position relative to the p-layer. This suggests that energy level alignment dominates over transport efficiency in carrier recombination. Finally, laser diodes with single and dual QWs exhibit comparable threshold currents, indicating that a well-optimized MQW system can achieve comparable performance to single QW devices.

These findings provide insights into optimizing MQW structures for improved carrier injection and recombination efficiency in InGaN-based optoelectronic devices, ultimately contributing to the development of more efficient high-power LEDs and LDs.

OD-Tue-P13* - Methods for temperature equalization in a one-dimensional array of nitride edge-emitting lasers

3. Optical devices
Dominika Dąbrówka[1]
Robert P. Sarzała[1], Maciej Dems[1]
[1] Institute of Physics, Lodz University of Technology

Abstract text: Laser arrays are key components of many modern technologies. Despite their widespread use across various fields, several challenges can limit their performance and application. One of the main challenges with laser arrays is effective thermal management. The simultaneous operation of multiple emitters generates significant heat, which can lead to excessive heating of the device. This, in turn, may alter the operating parameters of the array, reduce its efficiency, and shorten its lifespan. The significant amounts of heat generated also contribute to uneven temperature distribution across the individual emitters in the array, particularly within their active regions. This leads to uneven operation of the emitters, which not only switch on and off asynchronously but also emit light at different wavelengths, thereby degrading the output beam quality of the entire array. These issues are closely related to the effect of emitter mutual heating (thermal crosstalk), critically impacting the performance of laser bars. Therefore, precise management of heat flow between individual emitters in laser arrays is crucial for further improving their efficiency.

We propose a novel approach to address the issue of uneven temperature distribution in one-dimensional laser arrays of gallium nitride edge-emitting lasers emitting green light of 540 nm. Temperature uniformity in the one-dimensional array of edge-emitting lasers was achieved by adjusting the placement of the emitters within the array and modifying the dimensions of selected structural layers, without changing the overall dimensions of the device. Two possible modifications enable temperature equalization when combined with the optimized emitter arrangement. The first involves tailoring the size of the top gold contact, and the second entails adjusting the dimensions of the gallium nitride substrate. The proposed design alterations facilitate heat dissipation from inner emitters, ensuring an even temperature distribution across the array, without the need for specialized power supply or cooling systems. The proposed structural adjustments not only equalize the temperature distribution but also result in a slight reduction in the overall operating temperature. This, in turn, enables further improvements in the efficiency of laser arrays.

OD-Tue-P14 - Plasma-Isolated, Gain-Guided InGaN Laser Diodes – Advantages and Challenges

3. Optical devices

Szymon Grzanka[1]
Katarzyna Wolińska-Piotrowska[1], Szymon Stańczyk[1], Łukasz Piskorski[2], Tomasz Czyszanowski[2], Łucja Marona[1], Piotr Perlin[1]
[1] Institute of High Pressure Physics Polish Acadamy of Sciences, Warsaw, Poland
[2] Institute of Physics, Lodz University of Technology, Łodz, Poland

Abstract text: Gain-guided lasers represent the simplest and most cost-effective alternative to index-guided counterparts. In this study, we propose the use of highly efficient oxygen plasma-induced isolation to fabricate laser diodes without any dielectric isolation layers such as SiO_2 or Si_3N_4. This approach simplifies laser diode processing to just photolithography and metal contact deposition.

We have fabricated such devices using MOVPE epitaxy on commercial GaN substrates and compared three ridge widths: 5 µm, 10 µm, and 20 µm. Interestingly, the emission of these lasers is dominated by the fundamental lateral-transverse mode, even in broader-area devices. This behavior is supported by theoretical modeling, which indicates that optical modes in gain-guided (ridge-free) lasers exhibit better discrimination between fundamental and higher-order modes than their ridge waveguide counterparts.

The lasers demonstrated a lasing threshold of approximately 6.5 kA/cm² for a 5 µm-wide contact stripe, decreasing to 4 kA/cm² for a 20 µm stripe. The operating voltage was around 4 V at 5 kA/cm², which is a satisfactory result. The threshold current of these devices is roughly twice as high as that of ridge waveguide lasers fabricated from the same wafer, aligning well with numerical simulations for this type of waveguide. The absence of a dielectric isolation layer could be crucial for achieving very low thermal resistance, particularly when operated in a flip-chip configuration. However, the relatively high threshold current currently makes continuous-wave (CW) operation challenging. This higher threshold is attributed to weaker lateral mode confinement and increased optical losses. To enhance the practicality of these devices, further efforts are needed to mitigate these issues.

OD-Tue-P15 - Insights into degradation processes in nitride laser diodes

3. Optical devices

Lucja Marona[1]
Przemek Wisniewski[1], Grzegorz Staszczak[1], Szymon Grzanka[1], Piotr Perlin[1]
[1] Institute of High Pressure Physics, Warsaw, Poland

Abstract text: This study investigates degradation mechanisms in nitride-based laser diodes, a technology that has reached a high level of maturity in fabrication but still lacks a comprehensive model explaining its failure processes. In previous research, we proposed a laser facet degradation mechanism driven by oxidation in water vapor-containing environments, which helps explain surface deterioration. However, surface effects alone do not fully account for the overall degradation of InGaN laser diodes. Point defects are believed to play a crucial role in device degradation, yet their identification and characterization remain challenging. Epitaxial growth parameters influence defect type and concentration, with cation and anion vacancies being the most likely contributors. In this work, we examine how the growth conditions of p-type GaN and AlGaN layers impact laser diode reliability. Our results show that quantum well (QW) optical emission efficiency strongly depends on p-type growth temperature, independent of Mg doping levels. We attribute this behavior to the migration of native p-type point defects toward the QWs. Additionally, we compare the lifetimes of conventional Mg-doped laser diodes with polarization-doped variants. Despite significant differences in Mg profiles, both types exhibit similar degradation behavior. These findings suggest that Mg doping is not a primary factor in the volumetric degradation of InGaN laser diodes.

OD-Tue-P16 - Performance improvement of GaN-based laser diode by TMAH solution treatment on m-plane sidewall ridge structure

3. Optical devices

Mengyang Huang[1]
Peng Zhang[2], Yenxian Yang[1], Jianjun Zhu[1], Shulong Lu[1]
[1] Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences
[2] School of Nano-Tech and Nano-Bionics, University of Science and Technology of China

Abstract text:
GaN-based laser diodes have been developed rapidly in recent years, but the hexagonal crystal system is not involved in the design of ridge waveguide structure for edge-emitting laser diode. In this study, m-plane is set to the orientation of the ridge sidewall of the GaN-based laser diode and etched by TMAH solution to improve the device performance, with the threshold current decreasing from 194 mA to 183 mA, and the slope efficiency increasing from 0.49W/A to 0.59W/A. Tilt and rough sidewall morphology after dry etching can be restructure by TMAH corrosion, accompanied by carrier injection efficiency improvement and internal loss reduction.

OD-Tue-P17* - Wavelength Tuning of Three-Terminal LED

3. Optical devices
Bo LU[1]
Hoi Wai CHOI[1]
[1] The University of Hong Kong

Abstract text: The quantum confined Stark effect (QCSE) in the InGaN/GaN multi-quantum wells (MQWs), which rises from built-in field in the strained wurtzite materials structure and leads to red shift of the emission wavelength, has been exploited to achieve spectral blue-shifts by formation of nanopillars to release the strain. Strain relaxation by fabricating arrays of nanopillars introduces the blue and green light-emitting pixel regions on one red InGaN/GaN wafer. However, this method meets increasingly difficulties in large scale production due to the associated high cost. A possible mechanism in quantum well LED with tunable wavelength by manipulating the electric field within the material has been proposed. By enhancing and weakening the QCSE effect in MQWs, the emission wavelength can be blue-shifted or red-shifted depending on the bias voltage.

This work demonstrates a three-terminal LED device with dimension of 100μm×100μm. High indium content InGaN/GaN LED wafer on sapphire substrate with peak emission wavelength peak of around 610nm was used as the starting material. Standard μ-LED fabrication process, including dry etching by Cl_2/Ar, passivation by PECVD TEOS SiO_2, Ni/Au evaporation by eBeam, RTA process for ohmic contact and Ti/Au for metallization, was applied to fabricate the horizontal structure. The third terminal was implemented by the comb figures with TEOS SiO_2 underneath, while the Ni/Au for current injection contact pGaN directly. The fabricated device exhibts IV and EL characteristics with turn on voltage at around 2.4V and wavelength blue shift at high voltage, when appling forward voltage on pGaN and nGaN. By tuning the bias between the third terminal and nGaN, the peak emission wavelength of the μ-LEDs is blue-shifted 6nm and red-shifted 1nm with applied field voltage in 25V and -25V, respectively.

The result shows a minor shift with the a large field voltage, which might be contributed to the horizontal electric field dissipation in material. A thin film InGaN/GaN LED device with vertical structure is proposed, future work on the new structure will bring us a step closer to achieve the tunable three-terminal LED devices.

OD-Tue-P18* - Enhanced Performance of GaN-based Light-emitting Diodes by Photoelectrochemical Etching and Transfer-printing Process

3. Optical devices

Huanqing Chen[1]
Zhi Li[2], Menglai Lei[1], Linghai Meng[1], Weihua Chen[1], Brian Corbett[2], Xiaodong Hu[1]
[1] School of physics, Peking University, People's republic of China
[2] Tyndall National Institute, Cork T12 R5CP, Ireland

Abstract text: Conventional laser lift-off methods, although widely used, are prone to film cracking and high roughness, and can only be used on transparent substrates such as sapphire.[1] In this study, we reported use of the photoelectrochemical (PEC) etching scheme to realize efficient lift-off of GaN membrane, and we also demonstrate transfer printing LED chips onto high reflectivity substrates as well as flexible substrates by PDMS stamp.

To achieve selective etching, 3 pairs of n-doped InGaN/GaN MQWs was inserted at the bottom of conventional LEDs (100*100 μm^2) as the sacrificial layer, and the PL wavelength was ~415 nm to fully absorb the 405 nm light from the illumination source during the PEC etching. The etching rate of the sacrificial layer is about 10 μm/min when the applied bias voltage is set to 3 V and the electrolyte (HNO_3) concentration is 0.5 mol/L.[2] AFM image shows that the surface roughness of the backside after etching is ~5 nm. Micro-Raman test shows that the average E_2 (high) mode frequency moves from ~569.2 cm^{-1} (before lift-off) to ~567.1 cm^{-1} after complete release, which is very close to the stress-free state of bulk GaN. Meanwhile, the PL spectra imply that the luminescence peaks of the sacrificial layer at the left shoulder and the GaN yellow band at ~500 nm disappear.

After fully undercutting of sacrificial layer, the LEDs were transferred onto a high reflectivity substrate coated with Al film and a 100 nm thick Intervia as bonding material. Fluorescence microscopy images showed that the active region of sample LED_{Al} was undamaged and the intensity was much greater than that of a conventional LED-on-sapphire. In addition, the electrical properties of sample LED_{Al} is also enhanced. The I-V curves of sample LED_{Al} show a reduction in forward voltage of 0.18 V (from 4.50 V to 4.32 V) at 20 mA, and a significant reduction in reverse leakage current from 2.8 μA to about 0.6 μA at -5V. Additionlly, thanks to the reuse of light emitted from the active region by the bottom mirror, the EL intensity of sample LED_{Al} increased by more than 57%. EL spectra at different injection currents show a decrease in the blue shift from 6 nm to 3 nm after transfer to the new target, indicating stress relief within the MQW. And Fabry-Perot cavity fringes appear at 452 nm and 466 nm even without the top mirror.

OD-Tue-P19 - Could InGaN UL play a dual role in blue light emitting diodes for both defect trapping and dislocation screening?

3. Optical devices

Yao Chen[1]
Anna Toschi[1], Jean-François Carlin[1], Nicolas Grandjean[1]
[1] École Polytechnique Fédérale de Lausanne (EPFL)

Abstract text: An indium-containing underlayer (UL) is essential to be introduced before the InGaN quantum well (QW) active region for the blue light emitting diode to achieve an internal quantum efficiency (IQE) above 80%. Our previous studies on the InGaN UL revealed the existence of certain surface defects (SDs) and suggested a defect trapping mechanism in this layer. Then we pinpointed those SDs likely to be nitrogen vacancies (V_N) created at the GaN (0001) surface during the high temperature growth of GaN buffer, a layer which is universally used in III-nitride-based optoelectronic devices as it provides superior crystal quality. However, the incorporation process of these SDs from the GaN buffer into the InGaN epilayer (UL or QW) remains unclear.

In this work, we will focus on studying the characteristic of the SD migration in the (In)GaN layer, emphasizing the different behaviours in their incorporation with and without indium. We will first show that the maximum IQE of an InGaN QW with the introduction of an UL, either GaN or InGaN, is predominantly determined by the SD equilibrium concentration at the surface of this UL. This equilibrium concentration of SDs is fixed by two factors: the growth temperature and the indium composition. Finally, to explain the affinity of SDs to InGaN layer and the detrimental impact of the SDs incorporate into the InGaN QW, we propose a divacancy formation mechanism between a V_N and an indium vacancy occurred upon the growth of the InGaN layer.

As all these studies are carried out on InGaN QWs grown on free-standing GaN substrates, where the dislocation density (~1×10^6 cm^{-2}) is significant reduced compared to GaN-on-sapphire substrates (~1×10^8 cm^{-2}), it is worth to verify whether the defect trapping mechanism of InGaN UL is universally applicable in a more complex system. The preliminary results show that, once the SDs are all incorporated into the InGaN UL, the size of the V-pits, controlled by the thickness of this InGaN UL, might play a role to push even further the IQE of the InGaN QW. This result suggests that the InGaN UL plays a dual role when a high dislocation density substrate is used.

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[2] Y. Chen, C. Haller, W. Liu, S.Y. Karpov, J.-F. Carlin, N. Grandjean, Appl. Phys. Lett. **118,** 111102 (2021).

OD-Tue-P20* - Super retina TFT based full color microLED display via laser mass transfer

3. Optical devices

Xu Yang[1]
Jinchai Li[1], Zhaoxia Bi[2], Cheng Li[3], Kai Huang[1], Junyong Kang[4], Rong Zhang[1]
[1] Fujian Key Laboratory of Semiconductor Materials and Applications, CI Center for OSED, Engineering Research Center of Micro-nano Optoelectronic Materials and Devices, Ministry of Education, Department of Physics, Xiamen University, Xiamen 361005, China; Future Display Institute of Xiamen, Xiamen 361005, China
[2] Future Display Institute of Xiamen, Xiamen 361005, China
[3] Future Display Institute of Xiamen, Xiamen 361005, China; School of Electronic Science and Engineering, Xiamen University, Xiamen 361005, China
[4] Fujian Key Laboratory of Semiconductor Materials and Applications, CI Center for OSED, Engineering Research Center of Micro-nano Optoelectronic Materials and Devices, Ministry of Education, Department of Physics, Xiamen University, Xiamen 361005, China

Abstract text: Micro-LED display is considered one of the most promising technologies for next-generation displays. However, the high manufacturing cost has been a major obstacle to its accessibility to the general consumer market. Mass transfer, an essential process to achieve cost-effective manufacturing, has not yet reached commercial maturity. Critical issues, such as micro-LED chips, transfer equipment, and process materials, need to be addressed for the mass transfer technology. In this work, we present a 1.63-inch full-color micro-LED display module fabricated using laser mass transfer, which has a pixel density of 403 pixels per inch. This is the highest resolution ever achieved in the industry using mass transfer technologies. The laser mass transfer is realized through three process nodes: laser lift-off, laser-induced forward transfer, and carrier bonding. Each node has been thoroughly explored to improve yields. Insights into the present progress and future development of laser mass transfer will be shared in this work.

Currently, 266 nm diode-pumped solid-state lasers face challenges in laser lift-off (LLO) for patterned sapphire substrate GaN-based micro-LEDs. These challenges include a narrow process window, chip fracture, and edge damage. To clarify the cause of these issues, we simulated the energy distribution at the interface between the PSS and GaN for a single micro-LED using the ray tracing method. A laser homogenization scheme was proposed, achieving high-quality substrate lift-off with a yield exceeding 99%.

For ultra-high pixel density micro-LED displays, we summarized the process flow of laser-induced forward transfer (LIFT) to fabricate at-pitch chips on carrier (ACoC). Key steps include:

1. Evaluating transfer adhesive types based on laser-adhesive interaction;
2. Correlating laser energy range with adhesive thickness for high-precision, high-yield transfer;
3. Using AOI/PL detection for in-situ repair of defective chips.

The influencing factors, such as transfer material properties, laser energy, and chip damage, were comprehensively evaluated and optimized. This improved transfer efficiency, precision, and yield. Transfer rates reached 36 million units per hour. The one-step transfer yield of GB-chips reached

99.87%, while that of R-chips reached 99.76%. Furthermore, the use of a 266 nm laser for repair resulted in a post-repair yield of 99.999%.

OD-Tue-P21* - Micro-LEDs Based on InGaN Quantum Dots Grown by Molecular Beam Epitaxy for Visible Light Communication

3. Optical devices

Haowen Hua[1]
Peng Zhang[2], Yi Gong[1], Ying Gu[1], Mengyang Huang[1], Shu Lu[1], Jianjun Zhu[1], Wenxian Yang[1]
[1] Key Lab of Nanodevices and Applications, Suzhou Institute of Nano-tech and Nano-bionics (SINANO), Chinese Academy of Sciences (CAS), Suzhou, Jiangsu 215123, China
[2] School of Microelectronics, University of Science and Technology of China, Hefei, Anhui 230026, China

Abstract text: Visible Light Communication (VLC) is a potential communication method in 6G. However, the development of micro-LEDs as receiving devices is slow due to material quality and device structure. InGaN quantum dots (QDs), as a promising and efficient material for micro-LED, are ideal for VLC. In this work, plasma-assisted molecular beam epitaxy (PA-MBE, Veeco Gen20A) was used to grow self-assembled InGaN QDs for the fabrication of green micro-LEDs. The InGaN QDs exhibited a high density of over 3.0×10^{10} cm^{-2}, along with good dispersion and uniform size distribution. Full M-plane hexagonal micro-LED-based photodetectors (μPDs) were prepared based on the TMAH sidewall repair work, and the optoelectronic and communication performances of four sizes of μPDs, namely, 5, 10, 20, and 50 μm, were comprehensively compared. The results show that the micro-LEDs based on InGaN QDs grown by MBE exhibit excellent wavelength stability with increasing injection current density, and the device bandwidth reaches 2.5 GHz. This work demonstrates the great potential of MBE-grown InGaN QDs micro-LED-based photodetectors for visible light communication.

OD-Tue-P22 - Leakage Current in Pyramidal GaN micro-Light-Emitting Diodes

3. Optical devices

Andrei Vorobiev[1]
Chih-Wei Hsu[1], Eric Tseng[1], Zahra Mohammadianrasnani[1], Ryan Page[1], Sachin Sharma[1], Christer Svensson[1], Ivan Martinovic[1], Per-Olof Holtz[1], Lisa Rullik[1]
[1] Polar Light Technologies AB, 58330, Linköping, Sweden

Abstract text: The exact understanding of mechanisms and reduction of the leakage current in the light-emitting diodes (LEDs) is of particular importance due to its potential impact on the device parameters, e.g. external quantum efficiency (EQE), and degradation reducing lifetime. The leakage current mechanisms have been extensively studied in the conventional planar GaN LEDs. However, very little is published on the leakage current in the emerging micro-LEDs (μLEDs) based on three-dimensional GaN structures grown by selective-area epitaxy [1].

In this work we present results of studies of the leakage current in the pyramidal μLEDs, based on the GaN/InGaN multiple quantum well structures grown by selective-area epitaxy, operating in the blue spectral range [2]. Our TEM analysis reveals presence of the net of threading dislocations at the apex of truncated pyramids penetrating through relatively thin pGaN layer. It is known that the threading dislocations may provide direct pathways for leakage current due to their electronic activity. The analysis of the growth mechanism indicates that the truncated apex is formed at the stage of the pGaN growth as a result of the growth rate anisotropy appearing in the presence of magnesium and hydrogen as transport gas. With the aim to reduce the growth rate anisotropy, we modified the pGaN growth conditions. This allowed for finalizing the pyramid apex without truncation.

Comparative analysis of the current-voltage characteristics of the GaN μLEDs formed on truncated and non-truncated pyramids allowed for extraction of the leakage current associated with the truncated apex. The leakage current was simulated in Comsol assuming enhanced conductivity of the p-GaN layer caused by the threading dislocations and is in good agreement with that obtained via experiments. The leakage current is much less than the total current even in truncated μLEDs above approx. 3 V, corresponding to turn-on voltage of the blue μLED, and hence has a negligible effect on the parameters, such as EQE. However, the constant leakage at truncated apex may cause degradation of the pGaN properties and, hence, reduction of the lifetime. Therefore, using the non-truncated pyramidal μLEDs is preferable.

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[2] S. P. Le *et al*., *Appl. Phys. Lett.*, **118**, 142102 (2021).

OD-Tue-P23 - Monolithically Integrated GaN MicroLEDs with Two HEMTs and One MIM Capacitor for AR and Smartwatch Microdisplay Applications

3. Optical devices

Ran Zhang[1]
Yuefei Cai[1]
[1] Department of Electronic and Electrical Engineering, Southern University of Science and Technology, Shenzhen, 518005, China

Abstract text: GaN microLEDs have been regarded as a good candidate for next-generation AR and smartwatch microdisplay due to its high brightness, fast speed and long lifetime. As the pixel size scales down to smaller than 2 mm and pixel density increases, directly bonding microdisplay with its silicon driven CMOS circuitry becomes almost impossible in terms of alignment accuracy, yield and easiness. Monolithic integration of microLEDs with GaN-based electronics has been a promising solution to handle the assembly challenges. Previously, we have reported monolithic integration of 8x8 HEMT-microLED arrays for a 1T0C passive-matrix (PM) microdisplay[1,2]. In this paper, we will report our latest research on monolithic integration of microLEDs with two GaN HEMTs and one metal-insulator-metal (MIM) capacitor to form a 2T1C circuit a new approach to integrate HEMTs with microLEDs. By using a selective area overgrowth approach, the microLEDs are directly overgrown on top of the AlGaN/GaN surface of HEMTs to form the driving transistor (T2) and microLED display pixel as shown in Fig.1 (b) and (c). The device layout, electroluminescence (EL) and output (I-V) performance of monolithically integrated HEMT-microLED device is characterized and displayed in Fig. 2. By utilizing the space between different HEMT-microLED devices, another HEMT acting as a switching transistor (T1) and MIM capacitor are further designed and fabricated as shown in Fig. 3. Currently, the bottom metal pad for MIM capacitor has already been finished. Dummy MIM capacitors with a 12 nm-thick HfO_2 dielectric layer have also been fabricated at a low temperature of 150°C to avoid possible degradation of Ohmic contacts of both HEMTs and microLEDs. At the time when ICNS 2025 conference starts, passivation, row interconnection metallization of individual pixels and modulation test of whole HEMT-microLED active matrix display are hopefully to be achieved and presented. The monolithically integrated microLEDs with GaN-based 2T1C devices enable a full GaN-based active matrix (AM) microdisplay, which is suitable for AR and smartwatch applications in near future.

OD-Tue-P24 - Monolithic Trichroic MicroLED Display with Selective Etched Nanopillars

3. Optical devices
Bo LU[1]
Wai Yuen FU[1], Hoi Wai CHOI[1]
[1] The University of Hong Kong

Abstract text: InGaN/GaN LED displays in the commercial market adopt two mainstreams, including mass transfer for prototypes μ-LED devices and color conversion materials converting blue light emission into longer wavelengths. With the development of market's demand of higher resolution, it has become increasingly difficult for these methods to meet the ultra-high standards due to the challenges in defining pixels with high precision, associated high cost and low yield rate. Alternatively, chipscale μ-LEDs with different emission colors can be used for full-color displays, which could be an elegant solution as it addresses the yield rate issue more conveniently. Strain relaxation by fabricating arrays of nanopillars introduces the blue and green light-emitting pixel regions on one InGaN/GaN wafer.

This paper demonstrates a planar 9×9 monolithic and trichroic μ-LED array with pixel size of 35μm×35μm and a pitch of 60μm, consisting of pixels with 100nm and 600nm dimensioned nanopillars and the unstructured pixel. A high indium content InGaN/GaN multi-quantum well (MQW) LED wafer on sapphire substrate with peak emission wavelength peak of around 570nm was used as the starting material. The strong QCSE effect in the InGaN/GaN MQWs structure was exploited to achieve spectral blue-shifts of emission wavelength by formation of nanopillars to release the strain. Ordered mono-layer silica nanosphere coating and mask transfer processes were introduced for selective high-depth nanopillars etching. Height of 1.5μm nanopillar array was achieved by using the nanosphere with a diameter of 125nm and 700nm for nano-patterning. Due to the low selectivity (~1:6) of silica nanospheres to GaN, a sacrificial layer of 70nm LPCVD a-Si was introduced to transfer the small nanosphere pattern into 200nm hard mask of PECVD oxide. After dry etching, polish with PECVD TEOS SiO_2 was implemented for planarization and metallization.

By relaxing the stress in nanopillars, the emission wavelength peak of the μ-LEDs is 20nm, 77nm and 94nm blue-shifted in CL, PL and EL spectra, respectively. Notably, EL spectrum indicates significant trichroic emission in pixels, from 585nm in bulk pixel to 561nm and 491nm in 600nm- and 100nm-nanopillar defined pixel with applied voltage in 2.6V, 3.5V and 4V, respectively, leading to trichroic color display monolithically integrated on a single chip.

OD-Tue-P25 - The role of In fluctuation in InGaN quantum wells in LEDs and how to tailor them with a SiNx interlayer

3. Optical devices

Markus Pristovsek[1]
Jeong-Hwan Park[1], Wong Kwon[1], Heajong Cheong[1], Hiroshi Amano[1]
[1] Nagoya University

Abstract text: Alloy and thickness fluctuations of InGaN quantum wells (QWs) can cause carrier localisation as demonstrated by various theoretical and experimental works. These fluctuations increase the emission wavelength via the quantum confined Stark effect (thickness) and the locally reduced bandgap (In content). In multiple QW, the strain-dependent In incorporation enhances these fluctuations. The fluctuations manifest as an increased red shift at low currents and a broadening of the spectral FWHM.

Recently, very long lateral carrier diffusion lengths have been reported in QW on GaN bulk substrates, reaching more than 10 µm at low excitation. This indicates little localisation and hence fewer fluctuations in near-perfect substrates which usually give very good efficiencies.

Finally, V-pits have been shown to enhance the wall-plug efficiency in LEDs via lowering the forward voltage. Hence, low threading dislocation patterned substrates incorporate extra layers to deliberately generate V-pits. The V-pits will also affect the QW nearby.

First, we have investigated four InGaN QWs with different In contents by Atom Probe Tomography (APT). With the limits of APT (20x20 nm sample area, <5% atom catchment rate) we found a Gaussian random distribution of In content from 8% to 30% In content. The relative width of the distribution was wider for lower In content. However, the absolute variation in In content was higher for higher content, i.e., a stronger localisation in the 30% InGaN QW.

Additionally, we introduce a controlled disturbance of the QWs using an in-situ SiN interlayer with fractional coverage before the first GaN barrier. The SiN interlayer induces additional V-pits and at higher coverages larger defects in AFM. However, the PL intensity and external quantum efficiency (EQE) increased ~1.5x with the SiN interlayer with a red-shift of the emission.

The induced fluctuations in the InGaN QWs localise the carriers and prevent them from reaching the sides of our 80 µm circular test LEDs. Similarly, the localisation prevents more carriers from reaching point defects or dislocations and by this increases the EQE. Investigation of the SiN interlayer to enhance the EQE and localisation for QWs at longer wavelengths is ongoing.

OD-Tue-P26 - Investigation of Spatial and Spectral Electroluminescence of Blue and Green-Emitting InGaN/GaN Micro-Light-Emitting Diodes

3. Optical devices
Quang Trung Le[1]
Yuna Le[1], Byeong-U Bak[1], Youngwook Shin[1], Jaekyun Kim[1]
[1] Hanyang Univeristy, Republic of Korea

Abstract text: Self-emissive micro inorganic light emitting diode (μLED), such as GaN/InGaN MQWs-based μLED, have attracted industrial and academic interest in the applications of display, lighting, and optoelectronics owing to their exceptional properties, such as high efficiency and brightness, robust durability, instant response, effective energy performance, wide viewing angle, and broad range of working temperature. The performance of the epitaxial growth of the LED wafers mainly determines the optoelectronic characteristics, emission spectrum wavelength, and Full width at half maximum consistency. However, due to the difference in the atomic size induced lattice mismatch and the chemical dynamics as the decreased growth temperature with the increased indium composition, the consequent indium inhomogeneity causes the degradation of the luminous efficiency composed of the fluctuation in bandgap energy, the inconsistencies in the emission wavelength, and the broadening in the emission spectra.

In this study, EL distribution in GaN/InGaN MQWs-based Blue and Green μLEDs with the size of 50 μm × 50 μm is systematically investigated using confocal EL mapping. The spatial and spectral EL characteristics are examined at various injection current levels (0.05 μA – 5000 μA), revealing distinct differences in luminous inhomogeneity between the Blue and Green μLEDs. The Blue μLED demonstrates consistent emission across the entire area, whereas the Green μLED exhibits more complicated variation, reflected by a multimodal peak wavelength distribution, a broader full width at half maximum histogram, and the luminous intensity nonuniformity. We propose that these discrepancies are induced by random indium component fluctuations, which influence carrier dynamics. Based on the experimental results, the possible carrier dynamic mechanisms in the Blue and the Green μLED have been discussed. These findings present valuable insights into the design and efficient driving of GaN/InGaN MQWs-based μLEDs, paving the way for advancements in next-generation display technologies.

OD-Tue-P27* - Deep-Level-Mediated Red Luminescence in Trench-Architected Thick InGaN Films with 5nm low Blueshift

3. Optical devices

Haodong Zhang[1]
Zhizhong Chen[1], Zuojian Pan[2], Bo Shen[1]
[1] School of Physics, Peking University, Beijing, China
[2] Electrical and Computer Engineering Program, King Abdullah University of Science and Technology (KAUST), Thuwal, Kingdom of Saudi Arabia;

Abstract text: Micro-LEDs are regarded as the next-generation display technology with significant potential in AR/VR and flexible displays. However, red InGaN-based micro-LEDs suffer from severe quantum-confined Stark effect (QCSE) due to high indium composition and strong polarization fields, leading to large wavelength blueshift ($\Delta\lambda$) under increasing current injection. This compromises color accuracy and hinders full-color micro-LED implementation. Developing low-blueshift red InGaN micro-LEDs is thus critical.

By leveraging trench structures, we achieved red emission (648–643 nm, $\Delta\lambda \approx 5$ nm at 1–100 mA) using a 250 nm InGaN thick film as the active region. Trench structures, formed by stacking mismatch boundary (SMB), have traditionally been regarded as defects requiring suppression in InGaN epitaxial processes. However, our work demonstrates that controlled trench structures can enhance red light emission[1]. Unlike conventional quantum well structures, our innovative design employs trench-embedded InGaN thick films to enable red emission with exceptionally low blue shift.

The luminescence mechanism was systematically investigated through multi-scale characterization: STEM-CL mapping localized the red emission to trench sidewalls, while STEM-EDS ruled out high-indium-composition regions as the origin. TRPL analysis revealed comparable short lifetimes between the red emission (InGaN thick film) and green emission (pre-MQWs), suggesting deep energy level involvement rather than conventional indium-composition-dependent localization. DLTS identified a deep energy level with 0.9 eV activation energy, matching the energy difference between the red emission peak and the intrinsic InGaN emission. Since the energy positions of deep energy levels remain fixed, the recombination processes stay confined to these states even under increasing injection current, leading to ultralow blueshift.

This study establishes a new paradigm of deep-level-assisted radiative recombination through correlated microscale characterization and macroscale optoelectronic validation. Our findings provide critical insights for designing long-wavelength InGaN-based micro-LEDs, challenging conventional defect-avoidance strategies in nitride optoelectronics.

1.Pan, Z. *et al.* Efficient InGaN-Based Red Light-Emitting Diodes by Modulating Trench Defects. *Adv. Funct. Mater.* **34**, 2315781 (2024).

OD-Tue-P28* - Europium doped GaN quantum disks in GaN nanowires for efficient red LEDs realization

3. Optical devices

Alvaro Revilla-Martin[1]
Corentin Guérin[1], Fabien Jourdan[1], Bruno Gayral[1], Gwénolé Jacopin[2], Bruno Daudin[1]
[1] Univ. Grenoble Alpes, Grenoble INP, CEA, IRIG, PHELIQS, NPSC, 17 av. des Martyrs, 38000 Grenoble, France
[2] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France

Abstract text: Light-emitting diodes (LEDs) are widely used in modern displays, but achieving a monolithic integration of white LEDs using a single material group remains a significant technological challenge. Particularly, nitride semiconductors demonstrate excellent efficiency in the blue and green spectral regions. However, their performance is severely limited in the red spectrum. This limitation arises due to several intrinsic factors, including the large lattice mismatch between GaN and high-indium-content InGaN, as well as the Quantum Confined Stark Effect, which significantly reduces radiative recombination efficiency. These challenges make it difficult to achieve high-performance red emitters using standard nitride structures.

To overcome these intrinsic limitations, alternative strategies for red light emission must be explored. One promising approach is the incorporation of rare-earth metal ions as dopants, as they exhibit sharp and highly stable emission and absorption bands in the visible range. In the case of Europium (Eu), it exhibits emission at 621 nm, which falls within the red-light spectrum. Therefore, Eu-doped structures offer the potential for wavelength stability and improved efficiency without the need for excessive indium incorporation.

In this work, we investigate the optical and electrical properties of Eu-doped GaN nanowires (NWs) grown via molecular beam epitaxy (MBE). NW arrays offer several advantages over conventional layered structures, including the absence of extended defects such as dislocations, enhanced strain relaxation leading to a higher solubility limit for dopants, and a favourable geometry that improves light extraction efficiency. These properties make NW-based architectures an attractive platform for rare-earth doping and efficiency enhancement.

Electroluminescence measurements show the characteristic red emission of Eu-doped GaN NWs at room temperature, confirming the viability of this approach. The fabricated proof-of-concept LED devices demonstrate sharp red emission clearly visible to the naked eye.

OD-Tue-P29* - InGaN Red LED with Quasi-quantum Well Effect Based on High Al Composition in Electron Blocking Layer

3. Optical devices

Anda Cheng[1]
Lai Wang[1], Zhibiao Hao[1], Changzheng Sun[1], Bing Xiong[1], Jian Wang[1], Yanjun Han[1], Hongtao Li[1], Lin Gan[1], Yi Luo[1]
[1] Tsinghua University

Abstract text: Conventional long-wavelength InGaN red LEDs require high In compositions exceeding 35%, which is epitaxially challenging due to the 11% lattice mismatch between GaN and InN. To overcome these issues, we introduce a method that exploits the quasi-quantum well effect by incorporating a high Al composition electron blocking layer (EBL) (typically, the Al composition in EBL ranges from 5% to 20%) into the LED structure.

We utilized the commercial SiLENSe simulation software to model one single shallow red quantum well (In~25%) LED structure with varying EBL Al composition. We denote the first electron energy level as E_1, the first hole energy level as H_1. The results show that for the 10% and 27% Al-component LEDs, the E_1 values are -0.58 eV and -0.439 eV, while the H_1 values are -2.667 eV and -2.47 eV, respectively. The E_1-H_1 energy gaps for them are 2.087 eV and 2.031 eV. The AlGaN EBL, AlGaN capping layer and GaN barrier layer form a quasi-quantum well structure. Hence, the state density of the red well is higher, and the effective bandgap is narrower. Therefore, under the same injection conditions, this structure will result in a longer emission wavelength and higher intensity. It can be observed that with the continuous increase of the Al composition in the EBL, the quasi-quantum well effect is enhanced, leading to a progressive increase in the emission wavelength of the InGaN red LED. When the Al composition reaches 27%, further increments in the Al composition result in minimal changes in the wavelength.

Experimental electroluminescence (EL) testing of the micro-LEDs confirmed the simulation results, showing that the 15 μm micro-LED with a 27% Al composition EBL and ~25% In composition active region exhibited the longest emission wavelength at 625.8 nm and the highest wall-plug efficiency (WPE) of 3.2% at a current density of 1 A/cm^2. Notably, the WPE did not exhibit a monotonic relationship with the current density, suggesting complex carrier dynamics that are currently being investigated in our ongoing research.

This study provides a significant advancement in the design of InGaN red micro-LEDs, demonstrating that the quasi-quantum well effect induced by a relative high Al composition EBL is a promising strategy for achieving longer emission wavelengths while maintaining high optical efficiency.

OD-Tue-P30 - Investigation on the Enhanced Performance of N-polar InGaN-based Red LEDs

3. Optical devices

Kaige Xie[1]
Hongchang Tao[1], Shengrui Xu[1], Tao Zhang[1], Jincheng Zhang[1], Yue Hao[1]
[1] State Key Laboratory of Wide-Bandgap Semiconductor Devices and Integrated Technology, Xidian University, Xi'an 710071, China

Abstract text: InGaN-based red LEDs, which are essential for developing monolithic GaN micro displays, confront intrinsic material challenges including metastable epitaxial growth of high-indium-content quantum wells (In >30%), compositional inhomogeneity from indium segregation, and polarization-induced quantum confined stark effect [1], [2], [3]. Conventional Ga-polar red LEDs configurations exhibit severe efficiency limitations, while N-polar nitrides present reversed polarization-induced electric field, which results in enhanced electron-blocking ability and mitigated QCSE. However, the potential of N-polar InGaN-based red LEDs were not fully stimulated. In this study, APSYS was conducted to simulate the Ga-polar and N-polar InGaN-based red LED (λ~ 650 nm).

The LED structure is illustrated in Fig. 1(a), from bottom to top, the structure contains sapphire substrate, 3-μm-thick n-GaN (n=5×10^{18} cm^{-3}), 4-periods 2-nm-thick $In_{0.48}Ga_{0.52}N$/10-nm-thick GaN multiple quantum wells, p-$Al_{0.2}Ga_{0.8}N$ electron blocking layer (EBL) with doping concentration of 5×10^{18} cm^{-3}, p-GaN (p=5×10^{18} cm^{-3}) as hole supplier layer. Ga/N-polar structure was denoted as Sample A, and B respectively. Fig. 1(b)-(d) shows the device performance comparison for two samples. The LOP of Sample B has realized a 215% enhancement at 300 mA. The reduced voltage and higher LOP contributes to the higher wall-plug efficiency (WPE), and the WPE has increased from 0.9% to 3.8% at high current 300 mA. The higher peak electroluminescence intensity of Sample B has also indicated the enhanced performance of Sample A. As shown in Fig. 2. the electron barrier (φ_e) is elevated and hole barrier (φ_p) is reduced in the interface of MQWs/EBL, thus the much-suppressed electron leakage can be observed in Fig. 2(a). Benefited from the superior performance of N-polar LEDs, the EBL-free structure (Sample C) was proposed. For sample C, the LOP has further promoted to 60.3 mW at 300 mA (Fig. 3(a)). The simulation results demonstrate the potential of N-polar for realizing high-efficiency InGaN-based red LEDs.

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OD-Tue-P31* - Observation of ultraviolet photothermoelectric bipolar impulse in gallium-based heterostructure nanowires

3. Optical devices

Jinjie Zhu[1]
Qing Cai[1], Pengfei Shao[1], Haifan You[1], Hui Guo[1], Bin Liu[1], Hai Lu[1], Youdou Zheng[1], Rong Zhang[1], Dunjun Chen[1]
[1] Nanjing University, Nanjing, China

Abstract text: The photothermoelectric (PTE) effect represents a crucial pathway for directly converting light energy into electrical energy. Leveraging interaction between photothermal and thermoelectric processes, the PTE effect holds promise for applications in high-speed photoelectric energy harvesting and high-performance photoelectric detection. As semiconductor devices shrink to nanometer scales, the thermoelectric response of nanowires (NWs) structure is highly sensitive to surface conditions, making them invaluable for applications in fast-response PTE detection. Nevertheless, the transient response characteristics of UV-induced thermoelectric phenomena have been overlooked for an extended period. Exploring these phenomena could unveil applications in optical detection.

In this work, we develop a rapid-response UV electrochemical cell by constructing p-type GaN NWs arrays on silicon (Si) and integrating a GaON/GaN heterostructure interface through oxidative reconstruction. This device demonstrates distinctive PTE bipolar impulse detection characteristics. The GaON/GaN heterostructure NWs exhibit remarkable PTE effects under UV stimulation, showcasing rapid UV detection and high responsivity capabilities. The light-induced thermoelectric bipolar impulse generates at the moments of light on/off transitions dramatically enhanced the UV response speed of devices. Without external bias, the response/recovery time of the GaON/GaN electrochemical cell is reduced to 23.5% and 9.3%, respectively, compared to pristine GaN devices. Under weak UV light (0.2 mW/cm^2), the devices exhibit a notable 1900% increase in responsivity and a 266% improvement in specific detectivity. This enhancement in photoresponse characteristics due to the PTE effect is thoroughly expounded. Ultimately, the development of this fast-response UV electrochemical cell, based on the PTE bipolar impulse detection of GaON/GaN NWs, lays the foundation for optical communication systems with inverse encrypted communication capabilities. These advancements are poised to provide the possibility for applications in future UV photodetection in extreme environments.

OD-Tue-P33* - Revealing Physical Insights into Heterostructure Nitride Ultraviolet Photodetectors

3. Optical devices

Qing Cai[1]
Dunjun Chen[1], Rong Zhang[1]
[1] School of Electronic Science and Engineering, Nanjing University, Nanjing, China

Abstract text: The ultraviolet detection technology has significant demand in various civilian fields, including environmental monitoring, industrial combustion process control, power grid safety monitoring, deep space exploration, and medical ultraviolet imaging. With the development of ultraviolet detection technology and the increasing competition in military equipment, there is an urgent need to develop new high-sensitivity ultraviolet detection devices to detect extremely weak ultraviolet and deep ultraviolet target signals, meeting the substantial demand for this cutting-edge solid-state ultraviolet detection technology

This study introduces a GaON/GaN nanowire detector demonstrating novel bipolar thermoelectric pulses during 0 V UV exposure. The incorporation of GaON material with a high Seebeck coefficient significantly enhances the photothermal effect, and this heterostructure device also achieves bidirectional encrypted communication functionality. Simultaneously, we achieved controlled microplasma breakdown in AlGaN avalanche photodiodes with artificial mesa structures. At 107 V breakdown voltage, photocurrent surges while dark current remains ultralow (0.1nA), accompanied by mesa-edge blue luminescence. The device achieves record avalanche gain (3×10^6) and light-dark ratio ($>10^7$). Kelvin probe microscopy reveals the localized breakdown mechanism, showing how photocurrent-triggered avalanche events suppress noise while amplifying UV signals. This microplasma approach establishes a new paradigm for ultrasensitive photodetection.

OD-Tue-P34* - III-Nitride nanowires for flexible, transparent and synaptic devices

3. Optical devices

Min Jiang[1]
Yukun Zhao[1], Shulong Lu[1]
[1] University of Science and Technology of China; Suzhou; China

Abstract text: Gallium nitride (GaN) is one of the representative materials of the third-generation semiconductors, renowned for its excellent physical and chemical properties. However, relying solely on the inherent physical and material properties of traditional bulk GaN structures can sometimes limit device functionalities, making it difficult to meet the increasing demands in a multifunctional and complex electronic world, such as new-types of flexible, transparent, and synaptic devices. Si is the classic epitaxial substrate for III-V semiconductor nanowires; however, its opacity and lack of flexibility limit the application of GaN-based nanowires in novel devices. We propose a cost-effective and simple electrochemical delamination method for III-V semiconductor nanowires that can separate nanowire films from the original Si substrate used for growth within seconds, without the need for UV illumination or mechanical force. The key factor is the thin aluminum nitride (AlN) layer at the bottom, which serves as a buffer layer during epitaxy and as a sacrificial layer during etching. Utilizing the high etching selectivity of AlN relative to GaN, the bottom sacrificial layer can be quickly etched away without damaging the nanowires above. Based on this delamination process, we successfully fabricated highly transparent, highly flexible, and wearable bipolar photodetectors. Furthermore, using the persistent photoconductivity effect of GaN material, we successfully produced ultra-low-power synaptic devices that can be used for high-accuracy handwritten digit recognition. In summary, this delamination method for GaN-based nanowire films holds promise for mass production and various applications requiring high flexibility, high transmittance and dual-mode integration, including wearable smart electronics and synaptic devices.

OD-Tue-P35 - Performance improvements of AlGaN solar-blind ultraviolet phototransistor by N/Si-ratio-controlled in-situ SiNx passivation

3. Optical devices

Zhuoya Peng[1]
Shouqiang Yang[1], Xiulin Xie[1], Mian Wu[1], Zesheng Lv[1], Jiabing Lu[1], Hao Jiang[1]
[1] School of Electronics and Information Technology, Sun Yat-sen University, Guangzhou 510006, China

Abstract text: AlGaN based heterojunction field-effect phototransistors (FEPTs) taking the advantages of low operating voltage and high gain are preferred devices for high-sensitivity solar-blind ultraviolet (SBUV) detection. The FEPTs, however, are very susceptible to surface state effects leading to leakage current, unstable photogate voltage and persistent photoconductive (PPC) effect. In this work, we demonstrate an *in-situ* SiN_x passivation strategy with controlled N/Si ratio by adjusting source flow rate of metal-organic chemical vapor deposition. Our research reveals that the *in-situ* SiN_x passivation suppresses surface deep-level defects through two mechanisms: reducing oxygen impurities via oxygen insulation and occupying cation vacancies in AlGaN lattice via incorporated Si. The *in-situ* SiN_x prepared with a high NH_3/SiH_4 molar flow ratio at low SiH_4 flow rate, exhibiting a N-rich state, functions in both mechanisms. As a result, the *in-situ* passivation with controlled N/Si ratio shows an ordered atomic arrangement at the SiN_x/AlGaN interface with a surface roughness of 1.04 nm. The fabricated SBUV FEPTs demonstrate dark current as low as 30 fA at 5 V, a four-order-of-magnitude photocurrent decay within 20 s due to the suppression of PPC effect, and an enhanced 246/300 nm spectral rejection ratio of 2.0×10^4. Furthermore, the passivated FEPTs demonstrate robust stability in ambient conditions, maintaining consistent photoresponse over 360 days. This work provides a defect-engineering strategy via surface passivation to advance high-performance SBUV photodetectors for applications in air environments.

OD-Tue-P36* - Improvement of Cleavage Consistency via Stealth Dicing Strategy

3. Optical devices

Menglai Lei[1]
Linghai Meng[2], Jianbo Fu[2], Xiaodong Hu[1]
[1] School of Physics, Peking University, Beijing, China
[2] Guangxi Hurricane Chip Technology Co., LLC, Guangxi Zhuang Autonomous Region, China

Abstract text: GaN-based laser diodes (LD) play an important role in the field of display, lighting and laser processing. High-quality LD cavity mirrors are one of the key factors affecting the performance and lifetime of LD. Diamond-tip edge-scribing is used in the traditional cleavage process. However, the cleavage plane may deviate from crystallographic orientation and propagate to the inside of devices (Fig1.a1/a2). To solve this problem, we proposed a novel strategy which using laser stealth dicing (SD) method in skip-and-scribing mode. In this approach, cavity mirrors at different positions of a bar have maintained good parallelism (Fig1.b1/b2) and geometric deflection loss of LD decreased. Which results in better performance for those LDs that use SD method in the cleavage. Furthermore, a 1000-hour burn-in test was applied to TO56 packaged chips, the result shows the new cleavage method have the same stability and lifetimes as the traditional cleavage method.

OD-Tue-P37* - Efficient nonreciprocal acousto-optic modulation in GaN integrated photonic-phononic waveguides

3. Optical devices

Liang Zhang[1]
Yanan Guo[1], Jianchang Yan[1], Junxi Wang[1]
[1] Research and Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China.

Abstract text: The interactions between photons and phonons play a key role to bridge electrical and optical signals, enabling diverse applications ranging from quantum information to microwave and optical signal processing. Driven by advanced IC technologies, acousto-optic devices have recently been demonstrated to manipulate and control photons on integrated platforms. In these systems, optical nonreciprocity is an essential tool to control the direction of light flow, protecting optical components from the destabilizing effects of backscattered light. Here, we developed efficient nonreciprocal acousto-optic devices with gallium nitride on sapphire substrate. The unique capability to confine both optical and acoustic fields in sub-wavelength scales allows efficient acousto-optic interactions over long distances. This leads to the near-unity optical conversion efficiency with integrated acousto-optic modulators. With the unidirectional phase matching, we demonstrate the non-reciprocal propagation of optical fields with 3-dB bandwidth over 13 GHz. This work provides a robust and efficient acousto-optic platform, opening new opportunities for optical signal processing, quantum transduction, and non-magnetic optical isolation.

OD-Tue-P38* - GaN photocathodes with field-induced negative electron affinity: a novel pathway to electron sources

3. Optical devices

Stefano Marinoni[1]
Nicolas Tappy[2], Valerio Piazza[1], Anna Fontcuberta i Morral[1], Christian Monachon[2]
[1] Laboratory of Semiconductor Materials, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
[2] Attolight SA, Ecublens, Switzerland

Abstract text: Modern semiconductor nanotechnologies demand ultra-bright electron sources to enable high-resolution electron microscopy and lithography. These electron sources must exhibit long-term stability, straightforward intensity modulation, and outstanding coherence. With the expansion of time-resolved techniques, it is also highly desirable to design electron sources capable of generating both continuous and pulsed electron beams. Traditional metal cathodes, such as Schottky-type emitters, achieve high brightness through a small source but their conversion into laser-driven photocathodes for pulsed operation introduces significant limitations in stability and brightness [1-2]. Recent designs exploiting negative electron affinity (NEA) photocathodes based on caesium-activated semiconductor surfaces demonstrated excellent brightness and intensity modulation [3-4]. However, maintaining satisfactory performance requires frequent, in situ re-activation of the surface [4].

We explore a novel idea to induce NEA in p-doped gallium nitride (GaN) photocathodes without surface coating. We fabricate 40 µm tall GaN micro-pyramids of high-aspect-ratio with a scalable, top-down approach and sub-micron apex radius. Upon application of a voltage bias, the sharp morphology enhances the electric field around the pyramid apex. Our calculations predict field-induced NEA at typical fields used in commercial Schottky-type electron guns, or below. Experimentally, we validate this prediction by reproducing a laser-driven electron gun environment inside a scanning electron microscope. A UV laser is injected in the microscope and focused into a 4-um spot on the pyramid apex. Simultaneously, a biased nanomanipulator approaches the micro-pyramid surface at nanometric distances, inducing electric fields in the range of 1 GV/m. The photoemitted current is monitored during the experiment.

This work presents the conceptualization, prototyping and first experimental testing of field-induced NEA GaN photocathodes. We report benefits and challenges of this novel approach, which combines the established advantages of Schottky virtual sources with the flexibility of laser-driven semiconductor photocathodes.

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OD-Tue-P39 - TiS2 on GaN nanorod photoelectrode for accelerating photoelectrochemical hydrogen evolution reaction

3. Optical devices

Hoki Son[1]

[1] Changwon National University, Changwon 51140, Republic of Korea

Abstract text: In recent years, there has been a significant focus on advancing eco-friendly renewable energy technologies, driven by the potential to harness abundant resources such as water and sunlight. The shift from fossil fuels to renewable energy sources is gaining momentum, propelled by recent innovations. This surge in renewable energy technology development is particularly driven by progress in creating highly efficient solar-powered devices. Research in this field underscores the potential of photoelectrochemical devices to convert solar energy into chemical energy through artificial photosynthesis. In this study, we present the development and characterization of a novel photoelectrode composed of titanium sulfide (TiS2) deposited on gallium nitride (GaN) nanorod arrays for enhanced photoelectrochemical (PEC) performance. The GaN nanorods, known for their excellent chemical stability and wide bandgap, serve as a robust scaffold, while the TiS2 layer enhances visible-light absorption and charge transfer efficiency due to its narrow bandgap and high electrical conductivity. The TiS2/GaN heterostructure was synthesized via a controlled deposition process, ensuring uniform coating and strong interfacial contact. Morphological and structural analyses confirmed the formation of well-aligned GaN nanorods with a conformal TiS2 layer, while optical measurements revealed a significant extension of the absorption spectrum into the visible region. Photoelectrochemical testing demonstrated a marked improvement in photocurrent density compared to pristine GaN nanorods, attributed to the synergistic effects of enhanced light harvesting and efficient charge separation at the TiS2/GaN interface. This work highlights the potential of TiS2/GaN nanorod photoelectrodes as a promising candidate for solar-driven water splitting and other renewable energy applications, offering a pathway toward efficient and stable PEC systems.

OD-Tue-P40 - Enhanced Properties of Heavily Mg-doped GaN by Combining Thermal Annealing Processes in Ammonia/Nitrogen

3. Optical devices

Dan Yan[1]
Xuecheng Wei[1], Junxi Wang[1], Xuejiao Sun[1], Dan Yan[1], Ning Zhang[1]
[1] Institute of Semiconductors, CAS, Beijing, China

Abstract text: This study focuses on the heavily Mg-doped GaN in which the passivation effect of hydrogen and the compensation effect of nitrogen vacancies (V_N) impede its further development. To investigate those two factors, H ion implantation followed by thermal annealing was performed on the material. The evolution of relevant defects (H and V_N) was revealed, and their distinct behaviors during thermal annealing were compared between different atmospheres (N_2/NH_3). The concentration of H and its associated yellow luminescence (YL) band intensity decrease as the thermal annealing temperature rises, regardless of the atmosphere being N_2 or NH_3. However, during thermal annealing in NH_3 , the decrease in H concentration is notably faster compared to N_2. Furthermore, a distinct trend is observed in the behavior of the blue luminescence (BL) band under N_2 and NH_3 . Through a comprehensive analysis of surface properties, we deduce that the decomposition of NH_3 during thermal annealing not only promotes the out-diffusion of H ions from the material, but also facilitates the repair of V_N on the surface of heavily Mg-doped GaN.

The effect of a novel post-growth process, i.e. high-temperature thermal annealing process in NH_3, on the crystal quality, luminescence property, and electrical conductivity of the heavily Mg-doped GaN was studied. The experimental results showed that, compared with the traditional high-temperature annealing process in N_2, the high-temperature thermal annealing process in NH_3 can improve crystal quality in the heavily Mg-doped GaN, while promote the further effective doping of Mg acceptors, resulting in an enhancement of the intensity of the blue luminescence band in its photoluminescence spectra. The heavily Mg-doped GaN with significantly lower background electron concentration was obtained by combining high-temperature thermal annealing process in NH_3 with low-temperature thermal annealing process in N_2. This is because that the thermal decomposition products of NH_3 in the post-growth process can effectively reduce the concentration of shallow donor-type defects such as V_N and interstitial Ga atoms in the material, ultimately improving electrical conductivity of the heavily Mg-doped GaN.

OD-Tue-P41 - Nanowatt-Level Optoelectronic GaN-based Heterostructure Artificial Synaptic Device for Associative Learning and Neuromorphic Computing

3. Optical devices

Teng ZHAN[1]
Jianwen SUN[2], Jin LIN[1], Jinmin LI[1], Xiaoyan YI[1]
[1] Institute of Semiconductors, Chinese Academy of Sciences. Beijing, P.R. China.
[2] Tsinghua University. Beijing, P.R. China.

Abstract text: In recent years, research focusing on synaptic device based on phototransistors has provided a new method for associative learning and neuromorphic computing. A TiO_2/AlGaN/GaN heterostructure-based synaptic phototransistor is fabricated and measured, integrating a TiO_2 nanolayer gate and a two-dimensional electron gas (2DEG) channel to mimic the synaptic weight and the synaptic cleft, respectively. The maximum drain to source current is 10 nA, while the device is driven at a reverse bias not exceeding −2.5 V. A excitatory postsynaptic current (EPSC) of 200 nA can be triggered by a 365 nm UVA light spike with the duration of 1 seconds at light intensity of 1.35 μW/cm^2. Multiple synaptic neuromorphic functions, including EPSC, short-term/long-term plasticity (STP/LTP) and paried-pulse facilitation (PPF), are effectively mimicked by our GaN-based heterostructure synaptic device. In the typical Pavlov's dog experiment, we demonstrate that the device can achieve "retraining" process to extend memory time through enhancing the intensity of synaptic weight, which is similar to the working mechanism of human brain.

OD-Tue-P42* - Wafer-scale epitaxy of single-crystalline III-nitride semiconductors on amorphous SiO2/Si(100) substrates

1. Growth

Yimeng Sang[1]
Zhe Zhuang[2], Kun Xing[3], Xiangming Xu[4], Ying Wu[1], Feifan Xu[5], Tao Tao[5], Rong Zhang[6], Bin Liu[5]
[1] School of Integrated Circuits, Nanjing University, Suzhou, 215163, China
[2] School of Integrated Circuits, Nanjing University, Suzhou, 215163, China.
[3] School of Microelectronics, Hefei University of Technology, 193 Tunxi Road, Hefei 230009, China
[4] Materials Science and Engineering, Physical Science and Engineering (PSE) Division, King Abdullah University of Science & Technology, Thuwal 23955, Saudi Arabia
[5] School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China
[6] Xiamen University, Xiamen 361005, China

Abstract text: Advanced silicon-based integrated circuits and photonics are striving to achieve hetero-integration of III-nitride semiconductors not only on traditional crystalline substrates, but also on poly-crystalline or amorphous substrates. Currently, wafer or chip bonding is the method employed for this hetero-integration, imposing rigorous requirements on the fabrication and packaging processes. Another promising avenue for realizing this hetero-integration lies in the direct epitaxial growth of III-nitride semiconductors onto the desired substrates. Alternative materials, such as metals and two-dimensional (2D) materials, are currently being examined as potential buffer layers to establish the epitaxial relationship on non-single-crystalline substrates. Although it is possible to realize single-crystalline GaN films, the crystal quality is extremely poor compared commercial films. So far, achieving high-quality epitaxial films on non-single-crystalline substrates remains a significant challenge.

Here in this work, we introduce a unique mono-oriented 2D MoN buffer, converted from mono-oriented multi-layer MoS_2, to grow single-crystalline III-nitride semiconductors on an amorphous SiO_2 substrate by MOCVD. The 2D MoN buffer can present strong covalent bonds instead of weak vdW bonds at the initial nucleation, thus enabling precisely controlling in-plane orientation alignment for the epitaxy of AlN nuclei and subsequent GaN epi-layers. The fullwidth at half-maximum of X-ray rocking curve is measured as 0.19° and 0.32° for (002) and (102) plane, respectively. These values almost approach the typical levels of GaN grown on conventional single-crystalline substrates, much better than the previous results using other 2D buffers. The approach is also suitable for growing GaN on glass substrates. Finally, we used it to directly grow the AlGaN/AlN/GaN heterostructure and obtained an electron Hall mobility of 2240 $cm^2 V^{-1} s^{-1}$ at room temperature. The performance of the fabricated high-electron-mobility transistors (HEMT) is comparable to commercially available HEMT devices, implying great potential of our strategy for integrating III-nitride semiconductors with diverse platforms.

ED-Tue-P1* - Mechanism of Anomalous Breakdown Characteristics in MIS-HEMT Compared to Schottky-Gate HEMT for RF Applications

4. Electronic devices

Yuchen Qian[1]
Jiejie Zhu[1], Mengdi Li[1], Linjie Qin[1], Yichong Ding[1], Yiwei Wang[1], Yuxin Cheng[1], Boxuan Gao[1], Xiaohua Ma[1]
[1] Xidian University, School of Microelectronics, Xi'an, China

Abstract text: GaN MIS-HEMT are widely used in RF applications for their excellent stability. An anomalous breakdown behavior was observed: despite sharing the same carbon-doped GaN-on-Si epitaxial structure, Schottky-gate HEMT (SG-HEMT) exhibited higher breakdown voltage than MIS-HEMT devices, challenging the expected performance trend.

TCAD simulations of the electric field distribution indicate that the SiN insulating layer in MIS-HEMT effectively redistributes the barrier region electric field, which typically helps improve breakdown voltage. However, the quality of the insulating material becomes a crucial factor. The breakdown characteristics of MIS-HEMT show that the SiN layer effectively suppresses gate leakage, suggesting that the insulating layer has good quality. Therefore, the earlier breakdown of MIS-HEMT may not be due to the insulating layer quality, and it is necessary to further investigate whether buffer layer leakage contributes to the earlier onset of current-limiting breakdown.

Through TCAD simulations analyzing the electron concentration distribution at V_{gate}=−6V, V_{drain}=10V, we found that the vertical depletion region in MIS-HEMT is significantly smaller than in SG-HEMT. This indicates that the gate control ability of MIS-HEMT is weaker. Additionally, unintentional background doping during GaN growth introduces residual carriers, preventing complete device turn-off and forming a leakage path beneath the depletion region, leading to an earlier entry into current-limiting mode. Electrons preferentially follow paths with lower resistance. In MIS-HEMT, the insulating layer suppresses gate leakage, leading to an increased likelihood of electron transport beneath the depletion region. This suggests that under conditions of significant buffer leakage, the adoption of an MIS gate may further exacerbate buffer leakage.

It is worth noting that in power electronic devices, a larger gate length (L_g) and source-drain length (L_{sd}) provide better gate control, while the current density is reduced. Under the same epitaxial structure, power devices with an MIS structure do not exhibit significant premature current-limiting breakdown issues.

ED-Tue-P2 - Comparative Epitaxial Study of Si- and Ge-doped n+ (In)GaN Source/Drain Layers for Radio Frequency High Electron Mobility Transistors (RF HEMT)

4. Electronic devices

Sourish Banerjee[1]
Sachin Yadav[1], Alireza Alian[1], Hao Yu[1], Uthayasankaran Peralagu[1], Paola Favia[1], Erik Rosseel[1], Robert Langer[1], Anurag Vohra[1], Bertrand Parvais[1], Nadine Collaert[1]
[1] imec, Leuven, Belgium

Abstract text: The performance of AlGaN-based high electron mobility transistors (HEMT), designed to operate for beyond-5G wireless communication, is impacted by high contact and access resistance, limiting their operating frequency. To tackle this, we recently demonstrated record low contact resistance of degenerate Si-doped regrown n^+ (In)GaN source-drain layers by metal organic chemical vapor deposition (MOCVD) [1]. We reported higher carrier concentration (n) of n^+ InGaN compared to n^+ GaN under similar Si doping. However, we observed saturation of n beyond SIMS [Si] ~10^{20} cm^{-3}. On the contrary, Ge-doped n^+ GaN exhibits higher conductivity and mobility than Si for $n > 10^{20}$ cm^{-3}, useful in highly-doped contacts [2]. This work reports the performance of Ge- and Si-doped regrown MOCVD n^+ (In)GaN layers.

The n^+ (In)GaN depositions were performed over temperature (700–850 °C), pressure (200–600 mbar), germane (GeH_4) (0.5–2x sccm), triethylgallium (TEGa) and trimethylindium (TMIn) flow (0.5–3x sccm) under constant ammonia. The growth rate (0.3–1.2 nm/min) was impacted by the V/III ratio and GeH_4 flow, with increasing GeH_4 forming particles and reduced film growth. Indium incorporation, crucial for improved electrical performance, was limited to 4 at. %, measured by X-ray diffraction and photoluminescence. Ge: $In_xGa_{1-x}N$ layers were only possible under low V/III ratio and highly diluted GeH_4, with 10^{20}–10^{21} at. cm^{-3} Ge from SIMS. Very high n (3×10^{20} cm^{-3}) and low ρ (3×10^{-4} Ω.cm) was obtained from Ge: $In_{0.04}Ga_{0.96}N$; in comparison, the best n, ρ from Ge: GaN was 1×10^{20} cm^{-3} and 8×10^{-4} Ω.cm, respectively. The surface morphology of the InGaN sample revealed hexagonal pits, characteristic of indium incorporation. In contrast, Si: $In_{0.12}Ga_{0.88}N$ layers provided comparable electrical performance.

Nanobeam electron diffraction (NBD) mapped the lattice mismatch of the regrown areas, with lower in-plane lattice constant detected in the GaN channel near the barrier. This is ascribed to the compressive stress imparted by a regrown Si: $In_{0.07}Ga_{0.93}N$ layer on the channel causing lower n and higher sheet resistance of the two-dimensional electron gas (2DEG). We shall complement these results with characterization of HEMT with Si- and Ge- doped source/drain regions.

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ED-Tue-P3 - Influence of Al fraction on gate leakage in AlGaN channel high electron mobility transistors on silicon

4. Electronic devices

Julien Bassaler[1]
Jash Mehta[2], Idriss Abid[2], Leszek Konczewicz[3], Sandrine Juillaguet[3], Sylvie Contreras[3], Stéphanie Rennesson[4], Fabrice Semond[5], Julien Pernot[1], Yvon Cordier[5], Farid Medjdoub[2], **Philippe Ferrandis**[1]
[1] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France
[2] IEMN, CNRS, Université de Lille, 59650 Villeneuve d'Ascq, France
[3] Laboratoire Charles Coulomb, UMR 221, Univ Montpellier, CNRS, 34095 Montpellier, France
[4] EasyGAN SAS, Rue Bernard Grégory, 06905 Sophia Antipolis Cedex, France
[5] Université Côte d'Azur, CNRS, CRHEA, rue Bernard Grégory, 06560 Valbonne, France

Abstract text: Ultrawide bandgap semiconductors offer new opportunities for power electronics, particularly in domains where high voltage operation and elevated temperature stability are required. In this context, AlGaN/AlGaN heterostructures emerge as promising candidates due to the higher critical electric field of AlGaN compared to that of GaN, which leads to better figures of merit, especially for high Al content [1]. In this work, we investigate the impact of the aluminum fraction on the leakage current through MIS (Metal Insulator Semiconductor) gate in AlGaN channel high electron mobility transistors (HEMTs).

AlGaN channel heterostructures were grown by ammonia molecular beam epitaxy on a Si (111) substrate. To investigate the effect of the Al fraction on the leakage current through the MIS gate stack, the Al fraction in the channel was set to 10 %, 30 %, and 60 %, and the respective Al fraction in the barrier was set to 60 %, 70 %, and 90 % in order to enable the formation of a 2-dimensional electron gas at the interface between both layers. SiN was used as a gate dielectric.

The AlGaN channel HEMTs were investigated in operation from 300 K to 600 K. By increasing the Al fraction into the channel, a reduction of the off-state drain current was observed. This trend is explained by a reduction of the reverse gate leakage current.

By comparing conduction mechanism models with experimental gate current, the dominant leakage mechanism was assigned to Poole-Frenkel emission (PFE) [2]. The PFE barrier heights were then extracted as a function of the Al fraction in the channel and a reduction is observed when the Al content increases. A model is proposed to explain this behavior.

The better understanding of the leakage mechanisms in AlGaN channel HEMTs resulting from this work could be used to improve the fabrication and the performances of these devices.

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ED-Tue-P4* - Negative Bias Instability of Thin-Barrier Gallium Nitride Metal-Insulator-Semiconductor High Electron Mobility Transistors

4. Electronic devices

Simei Huang[1]
Jiejie Zhu[1], Mengdi Li[1], Lingjie Qin[1], Huilin Li[1], Boxuan Gao[1], Zhiyong Liu[1], Xiaohua Ma[1]
[1] National Engineering Research Center of Wide Band-gap Semiconductor, School of Microelectronics, Xidian University, Xi'an 710071, China

Abstract text: AlGaN/GaN metal-insulator-semiconductor high electron mobility transistors (MIS-HEMTs) on silicon substrates have potential in high power and high frequency application for excellent performance. However, these devices have threshold voltage instability which degrades switching speed. While thin barrier layer can enhance gate control, it increases the risk of gate breakdown. Deep understanding of gate reliability about thin barrier GaN MIS-HEMTs is critical for practical applications.

This paper investigated negative bias instability and degradation mechanisms of SiNx/(7nm)AlGaN/GaN MIS-HEMTs passivated by low-pressure chemical vapor deposition (LPCVD) SiNx on 6-inch Si substrate. The experiments consist of two parts, negative gate voltage step-stress tests and constant negative gate bias stress tests.

In negative gate voltage step-stress tests, gate stress current of the device with L_G=1 μm sureges at $V_{gstress}$=-95 V due to inverse piezoelectric effect(IPE). However, the device with L_G=0.2 μm is affected by IPE at $V_{gstress}$=-30 V with noisy characteristics and increase of the stress current. It is found that IPE mainly affects off-state gate leakage current(I_{goff}). Traps in barrier layer or dielectric capture electrons at negative gate stress. But IPE surpasses trap effect when gate stress voltage exceeds a critical value. The barrier layer releases excess tensile stress through lattice fracture, resulting in new leakage paths and increase of I_{goff}. New leakage paths caused by IPE accelerate gate breakdown. Stress current of three terminals in device with L_G=0.2 μm increase due to gate breakdown at $V_{gstress}$=-40 V.

Negative bias stress tests with $V_{gstress}$=-10, -20 and -25 V were performed on devices with L_G=0.2 μm. The stress time is 2000 s and recovery time is 3000 s. During the stress time, positive threshold voltage(V_{th}) shifts are 0.158, 0.225 and 0.395 V, respectively. It is suggested that during negative gate bias stress, traps in barrier layer capture electrons from gate injection, resulting in positive V_{th} drift. In recovery time, electron detrapping is via thermal activated emission which causes negative V_{th} drift.

The reverse gate leakage current is dominated by trap assisted tunneling(TAT) mechanism at 298 K by fitting and the relevant trap energy is 0.24 eV. The dominant mechanism is unchanged under constant negative bias stress above.

ED-Tue-P5 - Noise Characteristics of AlGaN/GaN HEMTs with Different Al Mole Fraction

4. Electronic devices
Yeo Jin Choi[1]
Ki-Sik Im[2]
[1] Department of Advanced Materials Science and Engineering, Kumoh National Institute of Technology, Gumi 39177, Korea
[2] Department of Green Semiconductor System, Daegu Campus, Korea Polytechnics, Daegu, Korea

Abstract text: AlGaN/GaN HEMTs are attractive for the high power and high frequency device application due to their superior material properties. Al mole fraction in AlxGa1-xN barrier layer plays an important role of the variation of the 2DEG density in AlGaN/GaN heterostructure and the generation of dislocations in AlGaN barrier layer. In this work, we fabricate and characterize the AlGaN/GaN HEMTs with two different types of Al mole fraction (x = 0.13 and 0.28) using Low-frequency noise (LFN) measurement. The LFN is very powerful to study the material defects and to find the conduction mechanism. For device fabrication, the AlGaN/GaN HEMTs are defined by photo lithography and etched by RIE for mesa isolation. The ohmic metal stacks are deposited and then are followed by rapid thermal annealing. Final step is the deposition of Ni/Au gate metal. LFN measurements are conducted at the frequency of 4 ~ 1000 Hz, Vg of -4 ~ 1 V, and Vd = 0.1 V. From the drain current power spectral density (SId) versus frequency, two devices present 1/f noise properties. In addition, the device with high Al mole fraction shows high noise level due to the increased dislocation caused by the high lattice mismatch between AlGaN and GaN layer. When the normalized SId matches with (gm/Id)2, two devices are dominated by the carrier number fluctuations (CNF) noise mechanism. This is because the noise is originated by the trapping/detrapping at the AlGaN/GaN heterostructure. It is noticed that the device with low Al mole fraction exhibits the increased noise levels at relatively high drain current of 10-4 ~ 10-5 A. When adding the SRsd value of 5 x 10-3 Ω2·Hz-1, the increased SId/Id2 are well matched with CNF with source-drain resistance fluctuations. Finally, the extracted trap densities (Nt) from CNF noise model are 2.1 x 1018 and 4.9 x 1018 cm-3·eV-1 for the device with low and high Al mole fraction, respectively. The reason for the high Nt for the device of high Al mole fraction is due to the multiple trapping/detrapping of the increased carrier densities.

ED-Tue-P6 - Post-gate annealing effects on short channel GaN-on-Si HEMTs

4. Electronic devices

Elodie Carneiro[1]
Lyes Ben Hammou[1], François Grandpierron[1], Drew Hanser[2], Ming Pan[2], Soo Min Lee[2], Farid Medjdoub[1]
[1] CNRS-IEMN, Institute of Electronics, Microelectronics and Nanotechnology, 59650 Villeneuve d'Ascq, France
[2] Veeco Instruments Inc., New Jersey, USA

Abstract text: The electrical properties of GaN make it ideal for high-power millimeter-wave applications, but challenges like surface electron trapping in AlGaN/GaN HEMTs, caused by Schottky contact barrier height inhomogeneity, lead to breakdown voltage degradation, current collapse, and reduced output power. **This study investigates the effect of post-gate annealing (PGA) on short-channel AlGaN/GaN-on-Si HEMTs, focusing on trap states, threshold voltage stability, and current collapse mitigation.**

AlGaN/GaN epitaxial layers were grown on an 8" high-resistivity Si substrate by Veeco PROPEL® MOCVD reactor. The structure includes an AlN nucleation layer, AlGaN buffer layers, a 200 nm-thick doped $Al_{0.10}Ga_{0.90}N$:C layer, a 150 nm-thick GaN channel layer, a 20 nm-thick $Al_{0.25}Ga_{75}N$ barrier layer, and a 2 nm-thick GaN cap layer. Device fabrication involved Ti/Al/Ni/Au ohmic contacts, rapid thermal annealing, isolation by implantation, and Ni/Au Schottky gate formation with L_G = 80, 140, 250, and 500 nm. Samples were annealed at 400°C for 10 min to assess PGA effects. Transfer characteristics up to V_{DS} = 20 V show identical drain-induced barrier lowering (DIBL) with and without PGA for L_G = 500 nm. However, for L_G = 80 nm, DIBL reduced by half, from 81 mV/V to 42 mV/V, indicating improved electrostatic control. A systematic threshold voltage (V_{TH}) shift to the right with PGA, attributed to a modified interface charge distribution and trap states. Open-channel pulsed I_D-V_{DS} measurements for L_G = 80 nm with PGA showed a 10-point reduction in current collapse, confirming an improvement in charge trapping and surface states near the gate. Dual-sweep capacitance–voltage (C–V) measurements at 1 MHz revealed hysteresis in the open-channel region for unannealed devices (L_G = 500 nm and L_G = 80 nm), while no hysteresis was observed for annealed gates, validating PGA's trap-state passivation effect.

These findings highlight PGA's role in enhancing device reliability and mitigating charge trapping, making this process step crucial for next-generation high-frequency AlGaN/GaN-on-Si HEMTs.

ED-Tue-P7* - Investigation of carrier transport and recombination processes in p-NiO gate AlGaN/GaN HEMTs under gate bias

4. Electronic devices

Yanghu Peng[1]
Hui Guo[1], Huaize Liu[1], Fangfang Ren[1], Youdou Zheng[1], Rong Zhang[1], Dunjun Chen[1]
[1] Nanjing University, Nanjing, China

Abstract text: The p-NiO gate AlGaN/GaN HEMTs have shown promising potential in high-power switching applications due to their superior electrical properties. As the gate stack, the p-NiO/AlGaN heterojunction exhibits a typical type-II "staggered" band alignment with a large band offset. In this case, the carrier transport and recombination processes in the p-NiO gate HEMTs are expected to differ from those in the p-GaN gate HEMTs. Investigating these processes, which haven't been studied yet, is crucial for further improving the performance of the p-NiO gate HEMTs.

In this work, carrier transport and recombination processes in the p-NiO gate HEMTs (Fig.1 (a)) were investigated by analyzing their electroluminescence (EL) with photoluminescence (PL) spectrum as a reference. As shown in Fig.1 (b) and (c), red luminescence (RL) with a peak at 1.9 eV was captured when gate bias exceeded 4 V, which was verified to originate from the tunneling-enhanced interface recombination of injected holes from the gate metal and spilled electrons from the 2DEG channel at the type-II band aligned p-NiO/AlGaN heterostructure interface. Under higher gate bias, holes were further injected into the GaN buffer layer through Poole–Frenkel (PF) emission with an activation energy of 0.6 eV, producing ultraviolet luminescence (UVL) and yellow luminescence (YL) as displayed in Fig.1 (b) and (d), corresponding respectively to the band-edge emission and defect-assisted radiative recombination of GaN.

Temperature-dependent I_G-V_{GS} measurements were also conducted. As shown in Fig. 1(f), the Generation-Recombination (G-R) current is the dominant gate conduction mechanism under both low forward bias and reverse bias. As the forward bias increases, the p-NiO/AlGaN/GaN PIN heterostructure diode is turned on, so the dominant gate conduction mechanism transitions to ohmic conduction. As the reverse bias increases, trap-assisted tunneling (TAT) gradually becomes the dominant gate conduction mechanism, which can be attributed to the type-II band alignment at the p-NiO/AlGaN heterostructure interface.

ED-Tue-P8* - Investigating the Short Channel Effects and Scaling Capability between AlScN/GaN and AlInGaN/GaN HEMTs

4. Electronic devices
Hao Lee[1]
Yuh-Renn Wu[1]
[1] Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei 106319, Taiwan

Abstract text: This study simulates the gate length scaling of HEMT structures with AlScN and AlInGaN as barrier layers. Our simulation results demonstrate that the f_T peak in the AlScN barrier case is 245.4 GHz, which is 16% higher than the 210.9 GHz observed in the AlInGaN barrier case during scaling. This improvement is mainly attributed to the higher 2DEG in the device.

The HEMT structures we employed for simulation use AlScN and AlInGaN as barrier layers with the same device configuration. The structure includes a Fe-doped GaN buffer and a 20 nm AlGaN back-barrier to prevent buffer leakage, a 30 nm channel to enhance electron confinement, a 1 nm AlN interlayer, and a 2 nm GaN cap layer. The resulting 2DEG concentrations are for the AlScN barrier case and for the AlInGaN barrier case, while the electron mobility remains for both cases. The increase in 2DEG concentration leads to a reduction in **sheet resistance from 298.5 Ω/sq to 185 Ω/sq**, contributing to improved device performance.

We first fit the experimental measurements of the $Al_{0.73}In_{0.08}Ga_{0.19}N$ barrier case[1] and extract external parameters before simulating and predicting the RF performance of the $Al_{0.82}Sc_{0.18}N$ barrier case. The simulation covers gate lengths ranging from 200 nm to 30 nm. Under the same epitaxial structure conditions, the f_T peak for both the AlInGaN and AlScN barrier cases occurs at a gate length of 50 nm. However, the AlScN barrier case exhibits a higher f_T peak, with a saturation current reaching 3200 mA/mm, which is 1.6 times that of the 2000 mA/mm observed in the AlInGaN barrier case. Additionally, the R_{on} is reduced from 1.51 Ω·mm to 1.12 Ω·mm.

AlInGaN, as a barrier material, is considered capable of achieving a high 2DEG concentration while maintaining high mobility. On the other hand, AlScN, when lattice-matched, can provide an even higher 2DEG concentration[2] than AlInGaN due to its stronger spontaneous polarization, enhancing the performance of GaN HEMTs and making it a promising competitor.

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ED-Tue-P9 - Analysis of Trapping-Induced Transconductance Overshoot in the Transfer Characteristics of AlGaN/GaN MIS-HEMTs

4. Electronic devices

Tintumol Dennis[1]
Wesley Sampson[2], Spyridon Papadogeorgos[1], Arthur Collier[1], Abdalla Eblabla[1], Richard Hammond[2], Sinan Goktepeli[2], Khaled Elgaid[1]
[1] Centre for High Frequency Engineering, Cardiff University, Cardiff, UK
[2] IQE PLC, Pascal Close, St Mellons, Cardiff, UK

Abstract text: GaN due to its wide band gap, provides exceptional performance characteristics such as high saturation velocity, high breakdown voltages, excellent power handling, and reliable operation at elevated temperatures. However, meeting the demand for even higher power densities at higher frequencies with GaN HEMTs is hindered by challenges. These include material imperfections leading to trapping of charge carriers which degrades the device performance [1].

An abnormal overshoot in transconductance, attributed to trap-related phenomena, has been previously observed in devices with thin GaN channel layers [2]. The trapping phenomenon responsible for the overshoot in transconductance characteristics were analysed using the DCIV characteristics of AlGaN/GaN MIS-HEMTs fabricated on a 200 mm GaN-on-Si wafers. Transistors with varying device dimensions, including gate lengths (L_g) ranging from 1 µm to 5 µm, gate widths (W_g) from 10 µm to 30 µm, drift lengths (L_{gd}) from 1 µm to 5 µm, with and without gate field plates (GFP) were used.

A positive transconductance (g_m) overshoot was observed in the transfer characteristics of the measured device. The gm overshoot consistently occurs when gate voltage (Vgs) is 1.4 V above the threshold voltage (V_t), independent of W_g, L_{gd}, and GFP. Its dependence on the gate length suggests that the traps responsible for the overshoot are not located in the gate-to-drain access region but within the gate dielectric or at the gate dielectric/AlGaN barrier interface. The g_m overshoot is not observed until the drain-source voltage (V_{ds}) of approximately 10 V is reached. Longer-gate devices require a higher V_{ds} for the g_m overshoot to occur. Due to its dependence on sufficiently high V_{ds}, we suggest that g_m overshoot is due to impact ionisation leading to generation of minority carriers which are then captured into traps located either in the gate dielectric or at the dielectric/AlGaN interface.

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ED-Tue-P10* - Output Conductance Overshoot in AlGaN/GaN MIS-HEMTs

4. Electronic devices

Spyridon Papadogeorgos[1]
Wesley Sampson[2], Arthur Collier[1], Tintumol Dennis[1], Abdalla Eblabla[1], Richard Hammond[2], Sinan Goktepeli[2], Khaled Elgaid[1]
[1] Centre for High Frequency Engineering, Cardiff University, Cardiff, UK
[2] IQE PLC, Pascal Close, St Mellons, Cardiff, UK

Abstract text: AlGaN/GaN HEMTs offer excellent electrical properties focused on high gain, low noise, enhanced breakdown strength and high temperature operation in microwave and mm-wave domain. However, GaN devices suffer from trap states concentrated under the gate, in the buffer, channel and barrier layers, which degrade device performance. Trapping effects such as the kink in the drain-source current (I_{ds}) have been observed in the forward output characteristic of GaN HEMTs [1]. This work observed an output conductance overshoot (g_{ds}) and a physics-based explanation is proposed.

AlGaN/GaN MIS-HEMTs were fabricated on a 200 mm diameter GaN-on-Si wafer, with measured devices having 20 µm gate width (W_g), 1 gate finger and 1 µm gate-source spacing (L_{gs}). The gate length (L_g) and gate-drain spacing (L_{gd}) were varied between 0.5 – 2 µm and 1 - 5 µm, respectively. DC-IV characterisation was conducted with drain-source voltage (V_{ds}) swept from 0 – 30 V and gate-source voltage (V_{gs}) swept from Vt – 2 V to Vt + 9 V, where V_t is the device threshold voltage.

The observed g_{ds} overshoot occurs at a specific V_{ds} of 12.5 V for all measured V_{gs}. This phenomenon is unaffected by L_{gd} indicating that traps are not located within the gate-drain region, while its strong dependence on L_g proves the traps are situated below the gate. Trap activation at a specific V_{ds}, irrespective of V_{gs} implies that the traps are not located between the gate and the two-dimensional-electron-gas (2DEG) channel. Moreover, overshoot occurrence at low V_{ds} also confirms that traps are not positioned inside the buffer-layer. Therefore, the traps are situated in the GaN layer close to the 2DEG. With variations to V_{gs}, the trap phenomenon shifts in magnitude and the overshoot changes from positive to negative. Specifically, for V_{gs} close to V_t, traps assist the gate by decreasing the V_t which results in an increase of current density. However, as V_{gs} becomes more positive, electron-hole pair recombination occurs leading to a reduction in device current density. As the gate-source, gate-drain and drain-source electric fields do not affect the g_{ds} overshoot voltage, it can be concluded that it is controlled by the drain-to-substrate field and is dominated by acceptor traps in the GaN layer below the 2DEG.

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ED-Tue-P11 - Breakdown Voltage Anomoly in AlGaN/GaN Metal-Insulator-Semiconductor High Electronic Mobility Transistor

4. Electronic devices

Yichong Ding[1]
Jiejie Zhu[1], Mengdi Li[1], Yuchen Qian[1], Lingjie Qin[1], Xiaohua Ma[1]
[1] School of Microelectronics, Xidian University, Xi'an, China

Abstract text: Enhancement-mode (E-mode) AlGaN/GaN metal insulator semiconductor high electronic mobility transistors (MISHEMTs) are widely used in microwave monolithic integrated circuits (MMICs), power amplifiers (PAs) and other radio frequency circuits. During fabricating a E-mode device, we found that the breakdown voltage of the E-mode device with etched trentch gate is higher than the depletion-mode device with planar gate.

The process flow and the structure of the device is presented in Fig.1. From bottom to top, the structure materials are a Si substrate, a GaN buffer, a 150nm GaN channel, a 1nm AlN interlayer, a 7nm thin AlGaN barrier, a 1nm GaN cap layer, and a 10nm thick *in-situ* SiN. The region under the gate is etched with low damage for 6nm. By etching the barrier, the two-dimensional electron gas (2DEG) under the 200nm gate is depleted, forming the E - mode. The transfer characteristics of the device is shown in Fig.2.With a threshold voltage V_{th} of 0.2V, this device can operate in E - mode.

Fig.3 (a) shows the structure of conventional AlGaN MISHEMTs, which is fabricated using the same process flow except for the 6nm low - damage etching. The etching process reduces the distance between the gate and the channel, broadening the depletion region in the buffer and leading to a decrease in the leakage current in the buffer. The simulation results are presented in Fig.5. This results in an increase in the breakdown voltage after the etching process, from 31V to 37V (V_g = -8V).

It is also found that as the gate voltage changes from -6V to -10V, the breakdown voltage of the device increases. When -10V is applied to the gate, the breakdown voltage is 41V. This can be explained by the broadening of the depletion region as the reverse voltage increases, similarly to the mechanism mentioned before. The simulation results are presented in Fig.6.

This work presents a proper reason to anomaly that etched devices have better breakdown voltage than planar devices. Due to low gate leakage current and lower drain leakage current than planar device, the etched AlGaN/GaN MISHEMTs also have high power added efficiency (PAE). Fig.7 shows its power - added efficiency (PAE) at 3.5GHz with a gate voltage of 12V, reaching 70.57%. The low gate leakage current is attributed to the etching process, which forms a better interface.

ED-Tue-P12* - The Influence of Partially and Fully Depleted p-GaN Layer on Threshold Voltage Instability in p-GaN Gate HEMTs

4. Electronic devices

Xuan Liu[1]
Chao Feng[1], Junye Wu[1], Danfeng Mao[1], Rongxin Du[1], Xiaoping Wang[1], Kepin Wu[1], Yuhao Wang[1], Haolin Hu[1], Wei Zeng[1], David Zhou[1], Yuxi Wan[1], **Yanlin Wu**[1]
[1] Shenzhen Pinghu laboratory, Shenzhen 518100, China

Abstract text: To enhance the gate reliability of Schottky-type *p*-GaN gate HEMTs, reducing the annealing activation temperature of the *p*-GaN layer has been demonstrated as an effective approach [1]. While our previous studies have revealed the impacts of fully depleted (FD) and partially depleted (PD) *p*-GaN structures on subthreshold and on-state characteristics [2], the dynamic threshold voltage V_{TH} instability mechanisms governed by Mg activation concentration N_{Mg} remain non-comprehensively study. Three device configurations were fabricated: Wafer A (PD *p*-GaN, $N_{Mg} \sim 4\times10^{18}$ cm^{-3}), Wafer B (PD *p*-GaN, $N_{Mg} \sim 7\times10^{17}$ cm^{-3}), and Wafer C (FD *p*-GaN, $N_{Mg} \sim 0$). Gate stress experiments under forward and reverse biases reveal distinct evolution patterns of threshold voltage shift ΔV_{TH} versus stress voltage. For PD *p*-GaN devices, ΔV_{TH} monotonically increases with stress magnitude under both forward and reverse biases, yet lower Mg activation concentration N_{Mg} (Wafer B) significantly suppresses forward-stress-induced positive ΔV_{TH}. The band diagram analysis attributes this improvement to reduced electron trapping (i) and electron-hole recombination (ii) at activated-Mg-related traps. The FD *p*-GaN (Wafer C) device exhibits unique responses: ΔV_{TH} first slightly increases due to negligible Mg activation concentration to effectively mitigate electron trapping (i) and recombination processes (ii), followed by a pronounced decreases under high forward stress, which originates from hole accumulation (iii) induced negative ΔV_{TH} at high bias, while high reverse stress exhibits abrupt ΔV_{TH} growth from enhanced electron injection (iv) due to lower Schottky barriers height $q\Phi_{Sch}$ in FD *p*-GaN layer.

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ED-Tue-P13* - Investigation of Threshold Voltage Instability in AlN/GaN MIS-HEMTs under High-Field Stress and Temperature Variations

4. Electronic devices

Huilin Li[1]
Jiejie Zhu[1], Lingjie Qin[1], Simei Huang[1], Boxuan Gao[1], Xiaohua Ma[1]
[1] National Engineering Research Center of Wide Band-gap Semiconductor, School of Microelectronics, Xidian University, Xi'an 710071, China

Abstract text: AlN/GaN metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs) are ideal for radio frequency (RF) applications due to their excellent high-frequency performance and significantly reduced gate leakage current. However, threshold voltage (V_T) drift occurs under high-field stress and temperature variations, negatively impacting device performance. Therefore, investigating the mechanisms of V_T instability is crucial for improving device reliability. This study focuses on exploring the relationship between V_T drift and high-field stress, as well as temperature variations.

In this study, AlN/GaN MIS-HEMTs with ALD-Al_2O_3 and *in-situ* SiN as stacked gate dielectrics were analyzed. These devices, with gate length of 0.2 μm and source-drain spacing of 3 μm, achieved a maximum drain current of 1488 mA/mm and a peak transconductance of 384 mS/mm at V_{DS} = 10 V.

In one set of experiments focusing on V_T drift under high-field stress, stepwise drain voltages were applied to the MIS-HEMTs, with V_D ranging from 0 to 80 V in 5 V increments. Each stress condition was maintained for 2 minutes, followed by DC characteristic measurements. Three distinct phases of V_T behavior were observed: (i) At V_D = 0-30 V, electron injection from the gate occupied shallow-level traps in the device, resulting in a positive V_T shift (ΔV_T = +0.5 V). (ii) At V_D = 35 V, V_T experienced a sudden shift due to the activation of deep-level traps under the higher electric field. Then V_T stabilized between V_D = 35-65 V as the intrinsic traps became saturated (ΔVT < 0.01 V). (iii) At V_D = 70 V, another sudden shift in V_T occurred. This was caused by high-field-induced defects that generated additional traps, resulting in a renewed positive drift in V_T (ΔV_T = +0.1 V).

In another set of experiments focusing on temperature variation effects, the V_T drift was examined as the temperature increased from 225 K to 375 K. A negative V_T drift (ΔV_T = -0.3 V) was observed and investigated using the temperature-dependent gate leakage model of AlN/GaN MIS-HEMTs. This behavior was attributed to the gate leakage dominated by trap-assisted tunneling (TAT), which results in an increased 2DEG concentration in the channel under the gate.

This study offers valuable insights for enhancing the performance and reliability of AlN/GaN MIS-HEMTs under high-field and high-temperature operating conditions.

ED-Tue-P14 - Effects of the high pressure annealing on threshold voltages in GaN-MOSFETs

4. Electronic devices

Tetsu Kachi[1]
Takumi Hirata[1], Kenji Ito[2], Tetsuo Narita[3], Jun Suda[1]
[1] Nagoya University
[2] Nagoya University, Toyota Central R&D Labs., Inc.
[3] Toyota Central R&D Labs., Inc.

Abstract text: Effects of annealing pressure for a gate oxide of a lateral GaN-MOSFET were characterized. The fabrication process is as follows. N^+-GaN, p^+-GaN, and p^--GaN layers were grown by MOVPE on an n-type GaN substrate. Next, Si ion implantation was performed for the formation of the source and drain regions, followed by activation and N ion implantation for device isolation. Subsequently, an SiO_2 interlayer insulation film was deposited and etched on the gate region. On top of this, an AlN interface layer and AlSiO gate oxide with the effective thicknesses of 0.8 and 40 nm, respectively, were formed using plasma-assisted atomic layer deposition. Under atmospheric pressure and 400 MPa in N_2 with the same heating and cooling rates, post-deposition annealing processes were performed at 800°C for 60 min. Then, source, drain, gate and backside electrodes were formed. The gate length and width of the MOSFETs used for evaluation were 100 μm and 98 μm, respectively. The transfer characteristics showed that the drain current was equivalent for both the annealing at atmospheric pressure and at 400 MPa. The maximum field-effect mobility was also comparable, being 173 and 169 cm²/Vs, respectively. Meanwhile, the average threshold voltages V_{TH} at normal pressure and 400 MPa were 0.33 V and 0.85 V, respectively, and 0.52V higher at 400 MPa. This is thought to be due to a reduction in the fixed charge at the interface [1] by annealing at 400 MPa. The reduction in fixed charge was calculated to be 4.2×10^{11} cm^{-2}. Furthermore, a PBI (positive bias instability) test was performed to evaluate the shift in V_{TH} under positive bias stress. It has been reported that the AlSiO/AlN structure suppresses electron injection into the gate insulating film even after normal pressure annealing and exhibits excellent PBI resistance [2]. It was shown that the PBI was further suppressed with annealing at 400 MPa. The notable difference between normal pressure and 400 MPa annealing was the amount of H in the AlSiO film. At 400 MPa, the H concentration in the oxide film was $7x10^{20}$ cm^{-3}, about two orders of magnitude higher than at normal pressure. H atoms may terminate fixed charges at the interface and in the oxide film. This work was supported by the MEXT program (Grant no. JPJ009777). [1] K. Ito et al., Ext. Abst. 2023 IEEE IEDM, 26-2. [2] H. Iguchi et al., Appl. Phys. Lett. 125, 022104(2024).

ED-Tue-P15 - Investigation of scattering components in AlSiO/AlN/GaN metal-oxide-semiconductor field-effect transistors formed on polar and non-polar planes

4. Electronic devices
Kenji Ito[1]
Tetsuo Narita[2], Masakazu Kanechika[1], Hiroko Iguchi[2], Emi Kano[1], Nobuyuki Ikarashi[1], Kazuyoshi Tomita[1], Daigo Kikuta[2]
[1] Nagoya University, Nagoya, Japan
[2] Toyota Central R&D Labs., Inc., Nagakute, Japan

Abstract text: An improvement of a channel mobility of GaN metal-oxide-semiconductor field-effect transistor (MOSFET) allows realizing a highly-efficient power switching device. We have demonstrated high effective mobility (μ_{eff}) in a GaN MOSFET inserting a thin crystalline AlN interlayer (AlN-IL) deposited by plasma-enhanced atomic layer deposition at an AlSiO/*p*-type GaN interface [1]. This study compares electron scattering components in AlSiO/AlN/p-type GaN MOSFETs having polar *c*-plane and non-polar *m*-plane channels as functions of an effective field (E_{eff}) in channel, an acceptor concentration in a body layer, and a substrate bias.

Planar MOSFETs were formed on *p*-type GaN body layers grown on freestanding *c*-plane GaN substrates, while *m*-plane channels were formed on the trench penetrating n^+ source and p-type body layers on n^+GaN drain layers. Owing to the tetramethylammonium hydroxide treatment, atomically smooth *m*-planes were observed by transmission microscopy. Each gate insulator was composed of a 40 nm thick AlSiO and a few nm thick AlN-IL.

The E_{eff}-dependent mobilities were analyzed [2] for MOSFETs with both plane channels, where the AlN-IL thickness and the body concentrations were approximately 1 nm and (1–2) × 10^{17} cm^{-3}, respectively. The results indicate that the *c*-plane channel mobility limited by the roughness scattering (μ_{SR}) was approximately 35% higher than the *m*-plane one. In the high N_a regime over 10^{18} cm^{-3}, the difference in μ_{SR} is clearer. The μ_{eff} on *m*-plane decreased in the high E_{eff}, while that on *c*-plane showed little change. Based on the extracted μ_{SR} components on both planes, the limitation of μ_{eff} in the high E_{eff} were well reproduced for various N_a values and different substrate biases. These results suggest roughness scattering on the *c*-plane was suppressed compared to the *m*-plane. We previously reported on the limitation by roughness scattering in *m*-plane channels at high E_{eff} [1]. The possible mechanism was the remote channel effect induced by polarization field at the *c*-plane AlN/GaN interface. Since a power MOSFET is used in the large gate overdriving voltage, this effect can give an advantage for a MOSFET on the polar plane.

This work was supported by the MEXT program (Grant no. JPJ009777).

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ED-Tue-P16* - Current Collapse Measurements of AlGaN/GaN HEMTs at Elevated Temperatures up to 300°C

4. Electronic devices
Jeewoo Kang[1]
John Niroula[1], Tomás Palacios[1]
[1] Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract text: Gallium Nitride (GaN) high-electron-mobility transistors (HEMTs) are essential for high-frequency and high-power applications, making them crucial for RF systems, power electronics, and next-generation communication technologies. Despite their advantages in efficiency and power density, thermal packaging challenges and degradation mechanisms hinder their widespread adoption. While GaN HEMTs have been extensively studied up to ~150°C [1], high-temperature pulsed I-V measurements characterizing current collapse up to 300°C remain unexplored.

This study examines silicon nitride (SiN) passivated AlGaN/GaN HEMT performance, evaluating their suitability for high-frequency and high-power RF applications under extreme conditions. Prior work show that current collapse is lower at higher temperatures, mitigating electron trapping effects [1]. Additionally, SiN passivation techniques suppress current collapse and improve power efficiency in GaN HEMTs under high temperatures [2]. Through a combination of pulsed I-V and DC characterization ranging from 25°C to 300°C, we demonstrate a high-performing GaN device with a maximum drain current exceeding 1.2 A/mm, alongside minimal current collapse from 0% to 30%, depending on bias and thermal stress conditions. Interestingly, although the maximum current decreases with temperature, the current collapse (defined as $\Delta I/I_{no,stress}$) actually increases up to 200°C and then decreases at 300°C. This likely indicates trapping plays a significantly less role at high temperatures, possibly because carriers have sufficient thermal energy to detrap from surface states. To the best of the authors' knowledge, this is the first ever set of current collapse measurements above 200°C. Overall, our results provide insight into the correlation between thermal stress, charge trapping, and RF power efficiency, reinforcing the need for optimized passivation and thermal management strategies in next-generation GaN technologies.

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Acknowledgements: Device fabrication and characterization was conducted at MIT.nano. This work was sponsored in part by the Air Force Office of Scientific Research (AFOSR) under award no. FA9550-22-1-0367 and Lockheed Martin Corporation under award no. 025570-00036.

ED-Tue-P17* - Impact of gate orientation on DC and RF characteristics of GaN/AlGaN high electron mobility transistors

4. Electronic devices
Patrick Jonsson[1]
Jesper Berglund Eklind[1], Niklas Rorsman[1]
[1] Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg SE-412 96, Sweden

Abstract text: Piezoelectrically driven relaxation of atomic positions near the GaN/AlGaN heterostructure interface causes planar anisotropy in the band dispersions of the two-dimensional electron gas (2DEG) [1]. As a consequence, nonlinear transport properties at high electric fields demonstrate a ~5% increase in saturation current and up to ~22% decrease in the effective mass for ΓK compared to ΓM azimuths.

This study investigates the impact of this anisotropy on the DC and RF characteristics of GaN/AlGaN gate-oriented high electron mobility transistors (HEMTs). GaN/AlGaN HEMTs were fabricated with gate finger directions varied along the [11-20] and [1-100] axes in 30-degree increments, promoting current flow along the ΓK and ΓM azimuths. Preliminary results indicate that the drain current is generally higher for ΓK than for ΓM, with the current ratio between these azimuths increasing with bias voltage by ~2%. This disparity is also reflected in the transconductance of the HEMT, which differs by ~2-5%. Future investigations will aim to evaluate other parameters, such as gate velocity and S-parameters. These findings suggest that optimising the crystallographic orientation of GaN/AlGaN heterostructures could serve as an additional design parameter, which should be considered in the design and fabrication of high-power performance GaN HEMTs.

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ED-Tue-P18* - High conductive strained quantum-well AlN/GaN/AlN heterostructure on AlN templates grown by PA-MBE through interface engineering and strain modulation

4. Electronic devices

Guanlin Wu[1]
Jiajia Yao[1], Junshuai Xue[1], Jincheng Zhang[1], Yue Hao[1]
[1] State Key Laboratory of Wide Bandgap Semiconductor Devices and Integrated Technology, School of Microelectronics, Xidian University, Xi'an 710017, People's Republic of China

Abstract text: Ultra-thin strained quantum-well AlN/GaN/AlN heterostructures grown on AlN substrates/templates are highly suitable for next-generation high-frequency and high -power electronic devices. However, the significant interface roughness scattering caused by rough surface in strained GaN channel remains a critical bottleneck limiting the electron mobility. In this work, high conductive strained quantum-well AlN/GaN/AlN heterostructures with improved electron mobility and high sheet carrier density are successfully obtained on AlN-on-sapphire templates by plasma-assisted molecular beam epitaxy.

Here, metal modulation epitaxy is used to homoepitaxy of AlN buffer on AlN templates, to eliminate the aluminum droplets accumulation on AlN buffer. Simultaneously, by introducing graded aluminum-content AlGaN between AlN buffer and GaN channel, the fully compressive strain in GaN channel is partly relaxed, which improves the heterointerface quality of AlN/GaN heterostructure and thus results in high electron mobility. Furthermore, double-channel AlN/GaN are employed to enhance the sheet carrier density of two-dimensional electron gas. Through the strain modulation and interface engineering, high electron mobility of 691 cm^2/Vs with a carrier concentration of 3.03×10^{13} cm^{-2} are achieved at room temperature in the optimized AlN/GaN/AlN heterostructure, which are twice and 1.5 times higher than the controlled sample (301 cm^2/Vs and 2.05×10^{13} cm^{-2}) without adopting graded aluminum-content AlGaN and double-channel structure, respectively. Besides, the epitaxial quantum-well AlN/GaN/AlN heterostructure exhibits a smooth surface and step flow morphology with an root-mean-square roughness of 0.2 nm over a scanned area of 5×5 μm^2 measured by atomic force microscopy and a sharp AlN/GaN interface characterized by scanning transmission electron microscopy.

In addition, high electron mobility transistors are fabricated on the epitaxial AlN/GaN/AlN heterostructures, which exhibits a high drain current density of 1.4 A/mm and maximum transconductance of 165 mS/mm for a gate length of 150 nm and gate width of 50 μm. The approaches presented here provide a promising opportunity for applications of quantum-well AlN/GaN/AlN heterostructures in high-frequency and high-power electronics.

ED-Tue-P19* - Multi-Gate Finger Microwave GaN HEMTs on Si substrates with Individual Source Vias

4. Electronic devices

Lu Hao[1]
Zhihong Liu[1], Hanghai Du[1], Guangjie Gao[1], Wei Hu[2], Weichuan Xing[2], Hong Zhou[1], Jincheng Zhang[1], Yue Hao[1], **Xin Feng**[3]
[1] School of microelectronics, Xidian University, Xi'an, China
[2] Guangzhou Institute of Technology, Xidian University, Guangzhou,China
[3] Xidian University

Abstract text: GaN high-electron mobility transistors (HEMTs) on Si substrates have demonstrated excellent performance with low-cost advantages during recent years for microwave and millimeter wave applications. The airbridge technology is generally used to interconnect the source ohmic contact pads in a multi-finger RF transistor and bringing issues such as parasitic capacitance, complex fabrication process, product yields, and device reliabilities. The technology of individual source vias (ISVs) has been successfully introduced in GaN-on-SiC RF HEMTs, which shows the advantages of smaller parasitic source inductance, higher maximum stable gain and maximum available gain, better RF grounding. In this work, we fabricated multi-gate finger microwave GaN-on-Si HEMTs with individual source vias with excellent performance.

The epilayers of device include an AlN (4 nm)/GaN heterostructure grown on a 6-inch Si substrate by MOCVD. The fabrication of GaN-on-Si devices started from mesa isolation by ICP etching, followed by Ti/Al/Ni/Au metallization annealed at 850 ^{o}C for 30 s for ohmic contact formation. T-shape gates with L_g=0.25 μm were then fabricated using an EBL system and Ni/Au deposition. Then the wafer was thinned down to 50 μm, and individual back via holes under the source ohmic contact metal pads with dimensions of 10×36 μm^2 were created by the local removal of Si by deep ICP etch and III-nitride materials by ICP etch. Finally, the metallization of the backside was done with a thin metal seed layer of Ti/Au by sputtering and 6 μm-thick Cu by electroplating.

The fabricated device with 6×50 μm exhibits an $I_{d,max}$ of 880 mA/mm at V_g = 2 V, and a peak $g_{m,max}$ of 330 mS/mm. Pulsed *I-V* characterization shows a 13% collapse of the drain current at the condition of V_{gq} =-5 V, V_{dq} =0 V, and 25% collapse at V_{gq} =-5 V, V_{dq} =12 V. At V_d =8 V and V_g=-2.5 V, the f_T and f_{max} were measured to be 52 GHz and 65 GHz after deembedding. The load-pull measurement shows a power gain of 17.6 dB, a PAE of 41%, and a maximum output power density of 3.3 W/mm at V_d = 30 V, V_g = -2.6 V and CW 10 GHz. These results show the great potential for the technology of individual source vias in the application of GaN-on-Si microwave devices.

Acknowledgement: This work was supported by Guangzhou Wide Bandgap Innovation Center and Grant 2020YFB1807300, YJS2213, ZYTS24060, and 2020B010171002.

ED-Tue-P20 - Abnormal phenomenon of source-drain current of AlGaN/GaN heterostructure device under UV/visible light irradiation

4. Electronic devices
Yuebo Liu[1]
Jieying Xing[1], Zhisheng Wu[1], Yang Liu[1], **Baijun Zhang**[1]
[1] State Key Laboratory of Optoelectronic Materials and Technologies, School of Electronics and Information Technology, Sun Yat-sen University, Guangzhou 510006, China

Abstract text: AlGaN/GaN heterostructure has a huge application market in the fields of high-power electronics and high-frequency electronics due to the presence of two-dimensional electron gas (2DEG) and its large bandgap. While the large number of defects and traps in the AlGaN/GaN materials would damage the stability and efficiency of AlGaN/GaN devices. The surface states, which decided by the distribution of defects and traps on the surface, have great impact on the electrical characteristic of heterostructure devices. The light irradiation can change the surface states, which affects the characteristic of AlGaN/GaN heterostructure devices. In this paper, we observed an abnormal phenomenon that the source-drain current (I_D) of AlGaN/GaN heterostructure devices decreases under visible light irradiation. While the current increases under 390 nm light, whose photon energy is less than the band gaps of GaN and AlGaN, it still causes an increase of I_D. Base on the UV light irradiation, a decrease of I_D can still be observed when turn on the visible light. This abnormal phenomenon is related to the surface barrier height, the unionized donor-like surface states below the surface Fermi level and the ionized donor-like surface states above the surface Fermi level, and the physical mechanisms of this phenomenon were elucidated using energy band diagrams. For visible light, its photon energy is less than the surface barrier height of AlGaN layer. The electrons bound in the donor-like surface states below the Fermi level are excited and trapped by the ionized donor-like surface states between the Fermi level and the conduction band of AlGaN. The electrons trapped in ionized donor-like surface states show a long relaxation time, and the newly ionized donor-like surface states below the surface Fermi level are filled by the electrons tunnelling from the 2DEG channel at AlGaN/GaN interface, which causes the decrease of I_D. While for the UV light, when its photon energy is larger than the surface barrier height of AlGaN layer, the electrons in the donor-like surface states below the Fermi level are excited to the conduction band and then drift into the 2DEG channel quickly, which cause the increase of I_D. The data of theoretical simulation are in good agreement with the experimental results, verifying the above explanation.

ED-Tue-P21* - Gate leakage mechanisms and their compact modeling in p-GaN gate AlGaN/GaN HEMTs

4. Electronic devices

Carlo De Santi[1]
Andrea Benato[1], Nicola Modolo[1], Matteo Borga[2], Niels Posthuma[2], Benoit Bakeroot[3], Stefaan Decoutere[2], Gaudenzio Meneghesso[1], Enrico Zanoni[1], Matteo Meneghini[4]
[1] Department of Information Engineering, University of Padova, Padova, 35131, Italy
[2] IMEC VZW, B3001 Leuven, Belgium
[3] IMEC VZW, B3001 Leuven, Belgium and CMST, IMEC, Ghent University, B9052 Ghent, Belgium
[4] Department of Information Engineering and Department of Physics and Astronomy, University of Padova, Padova, 35131, Italy

Abstract text: AlGaN/GaN HEMTs with p-GaN gate are widely used devices for efficient high power switching applications. In order to estimate and model the static and dynamic performance, a correct understanding of the gate leakage is needed. In this work, we present a physical model, implemented in an improved ASM-HEMT compact model [1] and calibrated with experimental data, of the gate leakage characteristic up to high gate voltage (10 V), able to reproduce the output, transfer, leakage and capacitance behavior of the DUT [2].

Below the threshold voltage of the transistor, the leakage is probably limited by the conductivity of the p-GaN sidewalls, and due to its complexity and low relevance it will not be modeled here. [3]. Once the channel is formed ($V_G \approx 2.5$ V), the gate leakage is limited by the thermionic emission of electrons from the channel above the series of the barrier of the AlGaN/GaN conduction band discontinuity, and of the barrier of the internal field in the AlGaN barrier. When the gate voltage is increased further ($V_G > 6$ V), the electric field at the Schottky junction at the metal/p-GaN interface increases, and hole injection due to trap-assisted tunneling [4] takes place, increasing the gate leakage. At very high voltage ($V_G > 9$ V) an additional process further increases the leakage, modeled as the thermionic emission of the holes injected from the contact above the p-GaN/AlGaN interface into the channel. These results differ from the ones presented in [3] due to the presence in the latter of an engineered p-GaN doping, which changes the electric field profile and, therefore, which mechanisms are relevant and active in the various voltage ranges.

The final compact model, including these four processes and calibrated by means of experimental data consistently with the literature [5], is able to simultaneously model all transistor characteristics in the entire gate voltage range, improving the understanding of the gate leakage processes and providing an useful tool for computer-assisted circuit design and simulation tools.

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ED-Tue-P22* - Investigation of Environmental Influence on C(V) Characteristics of GaN MISHEMT Test Structures

4. Electronic devices

Benjamin Weber[1]
Michael Dammann[1], Heiko Czap[1], Peter Brückner[1], Martina Baeumler[1], Helmer Konstanzer[1], Rüdiger Quay[1]
[1] Fraunhofer IAF, Freiburg, Germany

Abstract text:

1. INTRO and TECHNOLOGY

Oxygen diffusion from intrinsic and extrinsic sources causes electrochemical oxidation of SiN and AlGaN, decreasing device lifetime under HTRB [1]. The study evaluates effects of passivation thickness, humidity and stress voltage on the CV characteristics of GaN MISHEMTs test structures (TS) to better understand the processes in HTRB stress tests.
Two AlGaN/GaN MISHEMT TS are compared. The technology of TS1 is described in [2] and there are 60 nm SiN between the gate and the semiconductor as dielectric layer for the MIS capacitor. The primary distinction of the other technology (TS2) is additional deposition of SiN passivation after gate metallization (total SiN thickness: either 325 nm or 825 nm). C(V) measurements assess the depletion voltage (parallel plate capacitor [3]) between the gate metal and the ohmic contact to contact the 2DEG.

2. HTRB STRESS TESTS

The GaN MISHEMT TS have gate length of 80 µm and width of 100 µm. The bias voltage is swept from 0 (accumulation) to −30 V (depletion) and back at 100 kHz.
Elevated humidity levels (85% RH) accelerate GaN HEMT degradation [4]. In HTRB tests, biases were constant (V_G = −20 V, V_D = 10 V) while humidity varied (0% to 85%) at 85 °C. After 70 h, samples at 85% RH showed the fastest degradation with ΔV_{th} of over 20 V. At 40% RH, a similar shift occurred after 200 h, while at 20% RH, it took over 1000 h. Low humidity conditions resulted in ΔV_{th} of 2 to 3 V, with nitrogen-exposed devices showing even smaller ΔV_{th}.
Off-state degradation is driven by the e-field. V_D was varied (5 to 15 V; 5 V steps) while V_G at −20 V. Initially, devices with V_D = 5 V degraded more slowly than those with V_D = 10 V and 15 V (up to 200 h). Eventually, all devices showed ΔV_{th} of about 20 V, indicating that the V_G = −20 V is the main stressor.
The thickness of the passivation layer is critical for protecting devices. TS1 & TS2 were compared under 85% RH/85 °C. The TS1 degraded faster (ΔV_{th} < 20 V after 70 h) than TS2, which showed ΔV_{th} of 2.7 V (+265 nm SiN) and 2 V (+735 nm SiN) after 1000 h.

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ED-Tue-P23* - Investigating the Role of Threshold Voltage Hysteresis in Switching Performance of Normally-Off AlGaN/GaN MIS-HEMT

4. Electronic devices

Shantveer Kanta[1]
Srinivasan Raghavan[1], Navakanta Bhat[1]
[1] Centre for Nano-science and Engineering, Indian Institute of Science, Bengaluru, India

Abstract text: This work presents a detailed investigation of a high threshold voltage (V_{th}) enhancement mode (E-mode) Al_2O_3/GaN metal-insulator-semiconductor high electron mobility transistor (MIS-HEMT) fabricated on a silicon (Si) substrate. The high V_{th} and V_{th} hysteresis are attributed to the charge storage characteristics within the Al_2O_3 layer. V_{th} hysteresis impacts the reliability of Al_2O_3/GaN HEMTs, yet its influence on switching characteristics is seldom explored. To assess the impact of V_{th} hysteresis on the switching characteristics, this work initially explores V_{th} hysteresis under (i) various gate stress voltages and their stress times, (ii) different gate pulse amplitude and time, and (iii) varying off-state starting gate voltages ($V_{GS,min}$). Moreover, the experimental analysis delves into switching characteristics under various $V_{GS,min}$. In the presence of V_{th} hysteresis, a lower $V_{GS,min}$ decreases V_{th} when the device turns on. This phenomenon leads to a reduction in the turn-on delay without affecting the turn-off delay. We demonstrate that V_{th} hysteresis does not detrimentally impact switching operations. Lastly, this work examines the influence of the input gate voltage frequency on the turn-on delay of normally-off Al_2O_3/GaN HEMT.

ED-Tue-P24* - CuOx as an alternative gate material for AlGaN/GaN high-electron-mobility transistors

4. Electronic devices

Aleksandra Wójcicka[1]
Oskar Sadowski[2], Maciej Kamiński[2], Wojciech Hendzelek[1], Justyna Wierzbicka[1], Veronica Gao Zhan[1], Aneta Gołębiowska[2], Anna Szerling[1], Andrzej Taube[1]
[1] Łukasiewicz Research Network-Institute of Microelectronics and Photonic, Al. Lotników 32/46, 02-668 Warsaw, Poland
[2] Łukasiewicz Research Network - Institute of Microelectronics and Photonics, Warsaw, Poland And Warsaw University of Technology, Institute of Microelectronics and Optoelectronics, Warsaw, Poland

Abstract text: Semiconducting oxides are an integral part of current wide-bandgap semiconductor-based microelectronic devices, as the flexibility in their synthesis allows materials with either hole or electron types of conductivity to be obtained, thus making the integration of p-n junction easier. A method that allows their electrical properties to be tailored to specific applications without the use of additional dopants while being deposited at room temperature is magnetron reactive sputtering. Therefore, it is possible to obtain films with a carrier concentrations ranging from 10^{14} to 10^{21} cm^{-3}, while the energy band gaps can vary between 2 and 4 eV. Due to these advantages, oxide-based materials, such as NiO or CuO_x are a promising candidate to replace conventional metallic gates in high-electron-mobility transistors (HEMTs), and even replace the p-GaN layer, thereby simplifying technological processes, particularly selective etching, while simultaneously reducing costs. To date, there are a limited number of studies on the use of oxide-based gates, especially CuO_x - this will be the object of the study presented.

In this work we obtained high-quality CuO_x thin films from a copper oxide target under various conditions using magnetron sputtering and applied them as an oxide-based gate in AlGaN/GaN HEMT with the source and the drain contact of Ti/Al/Ti/Au (20/50/20/50 nm) metal stack deposited by the same method and formed at 750°C in pure nitrogen. 100 nm-thick CuO_x layers have been characterized by various methods, particularly 4-point probe measurements, optical transmission, X-ray diffraction. The layers exhibit an energy gap of 2.09-2.31 eV, and the resistivities of the as-deposited thin films are maintained at 10^{-1} Ohmcm. Additionally, modifying the films properties allows control over transistor parameters, particularly threshold voltages. CuO_x-gate allows to obtain the positive V_{th} shift reaching –0.8 V for as-deposited gate and typical gate leakage currents are as low as 10^{-6} A/mm in all cases, the $I_{on/off}$ ratio remains over 10^5. Additionally, the AlGaN/GaN HEMT with a conventional Ni/Au-gate was also fabricated and characterized for comparative analysis.

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ED-Tue-P25* - Hysteresis-Free GaN P-GIT Utilizing 2DEG as a Back Gate

4. Electronic devices

Jiaolong Liu[1]
Sen Huang[1], Qimeng Jiang[1], Xi Tang[2], Yingjie Wang[3], Xinhua Wang[1], Jianxun Liu[4], Qian Sun[4], Xinyu Liu[1]
[1] Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China
[2] the Institute of Physical Science and Information Technology, Anhui University, Hefei 230601, China
[3] Shenzhen Pinghu Laboratory, Shenzhen 518111, China
[4] the Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, Suzhou 215123, China

Abstract text: Integrating GaN-based Complementary Logic (CL) circuits into drive and control systems can further leverage the advantages of GaN power devices, enabling complex power conversion setups. Compared to the popular GaN Direct-Coupled FET Logic (DCFL), GaN CL demonstrates significant advantages in terms of static power consumption. However, advancements in p-channel GaN transistors, which are crucial for GaN CL, remain a formidable challenge, especially in terms of threshold stability and output performance. The threshold hysteresis observed in GaN p-FETs can be attributed to several factors, such as electron/hole traps induced by p-type doping, defects introduced during the etching process, and particularly interface states between the dielectric and p-GaN. In this study, we utilized the metal-like properties of the two-dimensional electron gas (2DEG) beneath the two-dimensional hole gas (2DHG) at the p-GaN/AlGaN interface to fabricate p-channel devices. The n-type ohmic contact serves as the gate of p-GITs, and since it is unaffected by bulk or interface states, the device exhibits no threshold hysteresis. The p-GITs exhibits a low on-resistance (R_{ON}) of 550 Ω·mm, a maximum drain current ($I_{D,MAX}$) of -2.6 mA/mm, and a high I_{ON}/I_{OFF} ratio of 10^7.

ED-Tue-P26 - Modified edge-gating geometry of AlGaN/GaN high-electron-mobility transistors for terahertz detection

4. Electronic devices

Maxim Moscotin[1]
Justinas Jorudas[1], Miroslav Saniuk[1], Irmantas Kašalynas[1]
[1] Center for Physical Sciences and Technology (FTMC), Vilnius, Lithuania

Abstract text: Terahertz (THz) technology has shown immense potential across various fields — including imaging, spectroscopy, and communication systems—but its full exploitation hinges on the development of high-performance detectors. Field-effect transistors, particularly those designed as TeraFETs, have emerged as promising candidates for THz detection [1]. In these devices, resonant detection is achieved by exciting plasma waves within the channel. The two-dimensional electron gas present in the channel acts as a plasmonic cavity, where interference of plasma waves results in resonant frequencies determined by the channel length and carrier density [2]. A critical challenge, however, is edge scattering. One promising approach to address this issue is to electrically narrow the effective channel width [3].

In this work, we demonstrate room-temperature THz detection using AlGaN/GaN-based TeraFETs with an electrically controllable effective channel width. Three gate configurations are implemented: (i) an edge-configuration (EdgeFET), where two gate electrodes approach the channel from the sides; (ii) a modified edge-configuration (m-EdgeFET), in which the two side-approaching gates are interconnected by a small bridge overlapping the channel; and (iii) a reference configuration (FinFET) with a solid gate electrode fully covering the channel.

Compared to the reference FinFET, the m-EdgeFET geometry exhibits an order-of-magnitude reduction in gate leakage current and a higher room-temperature THz responsivity up to 14 V/W. Furthermore, compared to the conventional EdgeFET, the m-EdgeFET shows a significantly lower threshold voltage — an important factor for practical applications.

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ED-Tue-P27* - TCAD based modeling of off-state degradation in AlGaN/GaN MOS-HEMTs

4. Electronic devices
Shani Tiwari[1]
Jaya Jha[1]
[1] Indian Institute of Technology (BHU) Varanasi

Abstract text: AlGaN/GaN HEMTs have been one of the most widely used III-N hetero-structure based devices for RF and power applications. However, these devices suffer from long-term reliability under high voltage operation when key performance parameters degrade. Some of these parameters include drain-to-source saturation current, threshold voltage, gate current, resistance in the linear region and operating frequency. In this work, three types of HEMTs are fabricated to decouple the effects of various degradation mechanisms in different parts of the device: i) oxide below the gate, ii) conventional MOS and iii) conventional access region passivated HEMTs. We have used Al_2O_3 in this work [1]. The devices are then subjected to off-state stress by applying -10 V at the gate and 20 V at the drain and I_{DS} versus V_{GS} was measured after certain intervals. We have used TCAD simulations to model the experimental pre-stress I_{DS}-V_{GS} data and after different applied stress times of 30, 60 and 180 minutes, using the following models: Lattice heating model, Selberherr's impact ionization model, Device degradation model devdeg, Gate current models hei and hhi and Lombardi CVT Model which is used to model the field dependent, concentration dependent and temperature dependent mobility. It was observed that the device degradation is mainly due to electron trapping at the Al_2O_3/AlGaN interface which causes a slight right shift in the threshold and significant reduction in the drain current. The degradation is most significant in conventional access region passivated HEMT where there is no insulation below the gate, as can be seen by the current levels and the fact that it also shows signature of hole trapping [2] as the current after 180 minutes of applied stress recovers back to the 30 minute stress value after a decrease at the 60 minute mark. Whereas, the other two devices do not show any signature of hole trapping at such low applied fields.

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ED-Tue-P28* - Trade-offs in mechanical and electrical properties of Silicon Nitride passivation for microwave Gallium Nitride High-Electron Mobility Transistors

4. Electronic devices

Jesper Berglund Eklind[1]
Patrick Jonsson[1], Niklas Rorsman[1]
[1] Chalmers University of Technology, Microtechnology and nanoscience, Gothenburg, Sweden

Abstract text: The mechanical and electrical properties of the Silicon Nitride (SiN_x) passivation layer affect both the small- and large-signal performance of Gallium nitride high-electron mobility transistors (GaN HEMTs)[1]. The mechanical stress is known to directly impact the mobility and electron sheet concentration in the 2-dimensional electron gas (2DEG)[2], while the electrical conductivity impacts the electron trapping at the surface[3] as well as the breakdown voltage[4]. Thus, both the mechanical and electrical properties of SiN_x on GaN-HEMTs have been individually investigated. However, how these in combination affect the device microwave performance is unknown.

In this study, the aim is to investigate the trade-offs of SiN_x mechanical and electrical properties on the GaN HEMTs microwave power performance. The SiN_x properties are varied by the dichlorosilane and ammonia (DCS:NH_3) flow ratios from 10:1 to 1:6 by low-pressure chemical vapor deposition (LPCVD). This resulted in stress per unit of film thickness increasing from 1.3 to 27.6 MPa/nm with the NH_3 flow rate. Furthermore, the films exhibit three resistive regions: thermal, Poole-Frenkel and resistive conduction. The resistive conduction (6.9 to 14.7 MΩm) and the corresponding critical electrical fields (0.93 to 6.91 MV/cm) increase with higher NH_3 flow.

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ED-Tue-P29* - Development of p-channel GaN FETs on extremely-low doped p-GaN with Mg-diffused Ohmic contacts

4. Electronic devices

Manuel Fregolent[1]
Biplab Sarkar[2], Shun Lu[3], Jia Wang[3], Hirotaka Watanabe[3], Kwon Woong[3], Carlo De Santi[1], Gaudenzio Meneghesso[1], Enrico Zanoni[1], Yoshio Honda[3], Hiroshi Amano[3], Matteo Meneghini[4]
[1] Department of Information Engineering, University of Padova, Padova, 35131, Italy
[2] Institute of Materials and System for Sustainability (IMaSS), Nagoya University, Japan, Department of Electronics and Communication Engineering, Indian Institute of Technology, Roorkee, India
[3] Institute of Materials and System for Sustainability (IMaSS), Nagoya University, Japan
[4] Department of Information Engineering, University of Padova, Padova, 35131, Italy; Department of Physics and Astronomy, University of Padova, Padova, 35131, Italy

Abstract text: P-type GaN devices are highly desired for the development of monolithically-integrated complementary logic circuits. Recently, post-growth thermal Mg diffusion was demonstrated for the realization of excellent ohmic contacts on p-GaN [1], [2] because of the formation of Mg-intercalated superlattices [3].

In this work we report the realization of p-channel GaN FET on an extremely-low doped (2×10^{17} cm^{-3}) p-GaN layer with three device designs: (a) Schottky-gate lateral FETs, (b) MOS-gate lateral FETs, and (c) Schottky-gate finFETs. The activation of the p-GaN layer was evaluated with C-V measurements, taht was in agreement with the SIMS data.

The Mg-diff based ohmic contacts were formed by first depositing and patterning metallic Mg; then the samples were annealed at 800 °C for 10 minutes. Mg residues were removed with boiling aqua regia. Then, conventional Ni/Au metal stack was deposited and sintered in O_2.
The DC characteristics of the devices highlight an excellent $I_{ON}/I_{OFF} > 2\times10^6$ and 4×10^6 with a V_{TH} of 18 V and 26 V respectively for devices (a) and (b). The fin-FET design was demonstrated to decrease the V_{TH} to 17 V, at the cost of a worsening of the $I_{ON}/I_{OFF} > 5\times10^4$.

The I_DV_{GS} of the p-MOSFETs devices (b) were characterized at cryogenic temperatures (120 K – 320 K). Results show that the ON-state current is strongly affected by the freeze-out of Mg dopants, because of the good agreement of the activation energy of the I_{DS} with the one of Mg acceptors; however, we proved that the V_{TH} remains stable for the explored range.

Channel mobility of the devices was extracted by calculating the contribution of the channel resistance to the overall $R_{DS,ON.}$ Despite the very low channel doping, the hole mobility results in the order of 0.24 – 0.30 $cm^2V^{-1}s^{-1}$. This result, consistent with prior reports [4] was confirmed by modeling the devices according to the textbook approach [5].

These results demonstrate that Mg-diffusion process leads to strong improvement for the realization of p-channel GaN devices, enabling devices on extremely-low doped layers.

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ED-Tue-P30* - Overcoming Trapping Effects in Buffer-Free QuanFINE GaN HEMTs towards Enhanced RF Power and Efficiency

4. Electronic devices

Lyes Ben Hammou[1]
François Grandpierron[1], Elodie Carneiro[1], Katir Ziouche[1], Etienne Okada[1], Ding Yuan Chen[2], Anders Lundskog[2], Jr-Tai Chen[2], Farid Medjdoub[1]
[1] CNRS-IEMN, Institute of Electronics, Microelectronics and Nanotechnology,Villeneuve d'Ascq, France
[2] SweGaN AB, Linköping, Sweden

Abstract text: QuanFINE buffer-free GaN-on-SiC HEMTs offer a promising platform for high-frequency, high-power RF applications, enabling ultrathin epitaxy, strong confinement, and efficient heat dissipation, key for aggressive scaling. Yet, despite removing the traditional doped buffer, downscaled QuanFINE HEMTs still suffer from trapping effects that degrade performance. We present a modified QuanFINE architecture that mitigates trapping while maintaining excellent confinement and boosting power performances.

Three AlGaN/GaN HEMTs using QuanFINE are studied. All feature an AlN nucleation layer, 150 nm GaN channel, 6 nm AlGaN (50% Al) barrier, and hybrid passivation (2 nm GaN cap + LPCVD SiN). Wafer A is the baseline; Wafer B adds an AlGaN back barrier (BB) below the channel; Wafer C uses only SiN passivation, omitting the GaN cap.

Pulsed I-V reveals significantly reduced current collapse in wafer B, especially at high V_{DSQ}, that stems either from the increased 2DEG to GaN/AlN interface distance (a known trapping site) or from the BB screening. Wafer B maintains a low DIBL of 32 mV/V vs. 22 mV/V for wafer A, proving confinement is preserved.

Drain current transients after 1 s filling ($V_{GS,fill}$= –6 V, $V_{DS,fill}$= 30 V) reveal four traps (T1-T4) in wafer A. T4 ($\tau \approx$100-1000 s, Ea≈0.15 eV) present in wafer A and C and previously linked to the GaN/AlN interface, was completely suppressed in wafer B, confirming the AlGaN BB effectiveness in screening this interface. Wafer C, lacking the GaN cap, exhibited no T1 (unlike Wafers A and B), implicating the GaN cap/SiN interface as its origin. While each modification independently suppresses a key trap, a combined structure integrating both the AlGaN BB and single SiN passivation could eliminate T1 and T4, the primary contributors to current collapse.

CW Load-pull at 40 GHz (V_{DS}=20V) demonstrate superior performance for Wafer B (with BB), achieving both higher PAE (47% vs. 39%) and increased Pout (2.30 W/mm vs. 1.55 W/mm) as compared to Wafer A. **This work paves the way for future highly scaled QuanFINE HEMT designs with minimized trapping effects, enabling next-generation high-power RF devices through strategic heterostructure and passivation engineering.**

ED-Tue-P31 - 0.1V On-voltage p-GaN Gated Anode Heterostructure Diode for Rectifying Radio Wave

4. Electronic devices

Naotaka Iwata[1]
Maria Emma Villamin[2]
[1] Specially Appointed Professor Iwata Laboratory, Research Center for Smart Energy Technology, Toyota Technological Institute, 2-12-1 Hisakata, Tempaku-ku, Nagoya, Aichi 468-8511, Japan
[2] Specially Appointed Professor Iwata Laboratory, Toyota Technological Institute, 2-12-1 Hisakata, Tempaku-ku, Nagoya, Aichi 468-8511, Japan

Abstract text: Conversion of weak radio waves in environment into electric power is a solution for power supplies to IoT devices. Rectifying such radio waves requires low on-voltage (V_{on}) diodes with low on-resistance (R_{on}). In addition, high breakdown voltage (BV) is also required for the wireless power transfer (WPT) application. We have been studying the gated anode diodes (GAD) with superjunction (SJ) utilizing p-GaN gate high electron mobility transistors (HEMTs). The purpose of this study is to develop the low V_{on} and R_{on} GAD with sufficiently high BV for rectifying radio waves.

The wafer used was grown by metal organic chemical vapor deposition on a silicon substrate, and composed of 40nm-thick Mg-doped (2×10^{19} cm^{-3}) GaN, 20 nm-thick $Al_{0.25}Ga_{0.75}N$, GaN channel, and buffer layers. The Mg-doped p-GaN gate on the AlGaN layer was formed and divided into two regions, as follows. First, the whole p-GaN gate (i.e., both regions) was formed on the AlGaN layer by inductively coupled plasma reactive ion etching (ICP-RIE) using $Cl_2/O_2/Ar$ (20/1/5sccm) with ICP and bias powers of 120 and 7W, respectively. This condition enables selective etching of GaN against AlGaN, since the etching rate ratio is 50 for GaN to AlGaN. Next, the cathode-side SJ region was thinned to 20nm by the ICP-RIE. The circular shape GAD with the gate width of 830μm was fabricated. The lengths of the gated anode and SJ were 25 and 4μm, respectively.

The fabricated circular GAD showed low V_{on} of 0.1V and diode current of 4mA/mm at 2V. The reverse leakage current and BV were on the order of 10^{-7}A/mm at 20V and about 100V at 0.1mA/mm, respectively. This reverse performance would be suitable for WPT application. The GAD and a p-n diode (fabricated on the same wafer) were in accordance with their device operations, i.e., GAD current is summation of HEMT and p-n diode currents. Then, the GADs were characterized with half-wave rectifier and voltage doubler circuits with RF signals of 1MHz and a 10kΩ load resistor. The GAD showed very low voltage rectification ability with 0.3V RF signal. The doubler circuit utilizing two GADs and capacitors also showed low voltage rectification with 0.3V RF signal. This doubler output would be suitable for charging battery of IoT devices.

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ED-Tue-P32* - Time-Dependent Gate Breakdown of Schottky p-GaN Gate HEMTs down to 15 K

4. Electronic devices

Siyuan Ye[1]
Sijiang Wu[1], Junting Chen[1], Jinjin Tang[1], Haohao Chen[1], Han Wang[1], Jun Ma[1], Xiaolong Chen[1], Mengyuan Hua[1]
[1] Department of Electrical and Electronic Engineering, Southern University of Science and Technology, Shenzhen, China

Abstract text: The Schottky-type p-GaN gate HEMT is a promising candidate for cryogenic applications due to its advantageous performance at low temperatures. However, its gate reliability is challenged by the accelerated time-dependent gate breakdown (TDGB) observed under cryogenic conditions. Despite its importance, the underlying breakdown mechanisms at low temperatures remain insufficiently explored. This work studies the TDGB behaviors of Schottky-type p-GaN gate at cryogenic temperatures. According to the TDGB tests, both the mean time-to-failure (MTTF) and predicted $V_{GS,max}$ for 10-year lifetime decrease as temperature drops from 300 K to 200 K, but maintains almost unchanged down to 15 K. This dual-mode dependence on temperature suggests different dominant TDGB processes across the measurement temperature range.

The TDGB is caused by hot electron bombardment on the metal/p-GaN interface, where the electrons gain energy through electric field acceleration in the p-GaN depletion region. Both the density and kinetic energy (KE) of electrons play a crucial role. The injected electron density and I_G are positively correlated. However, TTF and I_G exhibit the same temperature-dependent trend. Therefore, it is necessary to consider the KE of electrons, which is mainly modulated by electric field and mean free path (MFP). The electric field remains basically unchanged at the same V_{GS} because the threshold voltage shift during stress is negligible. Meanwhile, the increase of MFP at lower temperature reduces lattice scattering and leads to higher KE, which could explain the shorter TTF observed at 200 K compared to 300 K. The electron MFP is estimated with low-temperature mobility, extrapolated from high-temperature data. As for minority electrons, lattice scattering dominates scattering effects, causing drastic increase of MFP from 300 K to 15 K. It effectively enhances KE of electrons down to 200 K, but stops affecting KE at 15–200 K, because the MFP exceeds depletion region width (~31 nm) at about 200 K, rendering scattering effects negligible. As a result, from 15 K to 200 K the kinetic energy of electrons is independent of scattering and the MFP modulation. Thus, the TTF is almost independent of temperature at 15–200 K.

In conclusion, MFP should be carefully considered in the cryogenic studies of Schottky-type p-GaN gate degradation.

ED-Tue-P33* - E-mode AlGaN/GaN MIS-HEMTs on Si with 2.92 W/mm of Power Density at Vds = 12 V for Low-Voltage Applications

4. Electronic devices

Mengdi Li[1]
Jiejie Zhu[1], Yichong Ding[1], Yuchen Qian[1], Simei Huang[1], Xiaohua Ma[1], Yue Hao[1]
[1] School of microelectronics, Xidian University, Xi'an, China

Abstract text: Due to its excellent electrical performance, GaN HEMTs are widely used in high-voltage scenarios such as 5G communication, radar, satellite communication, and power electronics, while low-voltage application scenarios such as mobile communication terminals, micro-base stations, and wearable devices are more likely to adopt mature GaAs RF technology. However, due to the advantages of GaN HEMTs such as high output power density and high power addition efficiency, GaN technology also has great potential in low-voltage applications. GaN HEMTs on Si substrate offer significant advantages in terms of size, cost, and structure, making them a viable solution for low-pressure applications. This work reports high performance E-mode AlGaN/GaN MIS-HEMTs on Si substrate for low-voltage RF applications.

Fig. 1 shows the schematic cross section of the E-mode AlGaN/GaN MIS-HEMTs. The thin-barrier AlGaN/GaN and gate recess etching were adopted to achieve E-mode operation. In addition, the n^+-InGaN regrown ohmic contacts and the small source-drain spacing dimension structure were adopted to make the device more suitable for low-voltage RF applications. The PEALD-SiN gate dielectric was adopted to greatly decrease gate leakage current.

As shown in Fig. 2, a V_{th} of 0.64 V and a peak transconductance of 404 mS/mm were achieved. Moreover, an excellent off-state drain current density as low as 2.5×10^{-5} mA/mm at V_{gs} of −4 V and a high drain current on/off ratio of 5.4×10^7 can be observed. The devices demonstrate a maximum drain saturation current density of 1381 mA/mm at 5 V gate bias, a low on-resistance (R_{on}) of 0.84 Ω·mm, and a low knee voltage of 2.4 V. Fig. 5 shows the small-signal gain characteristics of the E-mode AlGaN/GaN MIS-HEMTs with a L_g of 0.2 μm obtained at V_{ds} = 8 V. A maximum f_T of 60 GHz and a maximum f_{MAX} of 123 GHz were achieved at V_{ds} = 8 V and V_{gs} = 2.1 V. The loadpull measurement was carried out at 3.6 GHz, and the operating low-voltages was 12 V. As shown in Fig. 6, a high peak PAE of 65.1% and a saturated P_{out} of 2.92 W/mm with a power gain of 15.63 dB were achieved at V_{ds} of 12 V. These results indicate that the E-mode AlGaN/GaN MIS-HEMTs on Si have great potential in low-voltage RF applications.

ED-Tue-P34* - High-efficiency Al2O3 /AlN/GaN MOS-HEMTs on 150-mm Si Substrate for Low-Voltage Applications

4. Electronic devices

Lingjie Qin[1]
Jiejie Zhu[1], Yuxi Zhou[1], Mengdi Li[1], Simei Huang[1], Huilin Li[1], Bowen Zhang[1], Xiaohua Ma[1]
[1] State Key Discipline Laboratory of Wide Band-Gap Semiconductor Technology, School of Microelectronics, Xidian University, Xi'an 710071, China

Abstract text: Benefitting from the material properties, such as wide band gap, high saturation velocity, and high critical breakdown field strength, GaN-based high electron mobility transistors (HEMTs) on silicon substrate have been widely used in radio- frequency (RF) and power applications. They show high performance in terms of frequency, efficiency, breakdown voltage, and output power, with low cost and easy integration. To meet the millimeter-wave and high-power requirements for low-voltage applications, the focus has been on scaled - down devices. AlN/GaN heterojunctions, which have higher spontaneous and piezoelectric polarization than other III-nitride material systems, have been used in high - frequency and high-power devices to improve frequency and power characteristics.

The *in-situ* SiN/AlN/GaN epitaxial materials were grown on 150-mm Si substrate by metal-organic chemical vapor deposition (MOCVD). From the top to bottom, a 3.0-nm *in-situ* SiN layer, a 4-nm AlN barrier layer, 150-nm un-doped GaN channel layer and 50-nm back barrier layer with Al composition of 0.06 were defined. The room-temperature Hall measurement shows low sheet resistance of 250 Ω/□, high electron sheet concentration of 1.70×10^{13} cm^{-2} and an electron mobility about 1430 $cm^2/V\cdot s$. In this work, the device has double gate fingers with a total gate-width of 100 μm, a source/drain spacing (L_{SD}) of 2 μm and gate length (L_G) of 0.2 μm.

We present Al_2O_3/AlN/GaN metal-oxide-semiconductor high electron mobility transistors (MOS-HEMTs) on silicon substrate, by using regrown ohmic method, demonstrating excellent transconductance and frequency characteristics. The MOS-HEMTs with 0.2-μm gate length (L_G) and 2-nm Al_2O_3 exhibit a small ohmic contact resistance less than 0.1 Ω·mm, a large ON/OFF-state current ratio of 10^8, a peak transconductance greater than 730 mS/mm, and a drain current approximately 1.6 A/mm. Therefore, high cut-off frequency (f_T) of 86 GHz and maximum oscillation frequency (f_{max}) of 140 GHz are obtained. The frequency figures of merit $f_T\times L_G$ is 17.2 GHz·μm and $f_{max}\times L_G$ is 29.6 GHz·μm at drain voltage (V_D) of 6 V, respectively. The large-signal radio-frequency (RF) output power characteristics demonstrated a high-power density of 0.9 W/mm and PAE of 72.71% at frequency of 3.6 GHz and drain voltage of 6 V.

ED-Tue-P35* - MmWave AlGaN/GaN HEMTs on a 6-inch Si Substrate with 150 nm T-gate Fabrication Process

4. Electronic devices

Xiaojin Chen[1]
Jin Zhou[2], Hu Wei[2], hanghai Du[3], Weichuan Xing[2], Weihang Zhang[2], Jincheng Zhang[3], Zhihong Liu[3], Yue Hao[3], **Xin Feng**[4]
[1] State Key Discipline Laboratory of Wide Band Gap Semiconductor Technology, Xidian University, Xi'an, China
[2] Guangzhou Institute of Technology, Xidian University, Guangzhou, China
[3] State Key Discipline Laboratory of Wide Band Gap Semiconductor Technology, Xidian University, Xi'an, China
[4] Xidian University

Abstract text: Silicon-based GaN High Electron Mobility Transistors(HEMTs) have demonstrated excellent performance due to their characteristics of large current, high breakdown voltage, and high output power. In this work, we have realized high-performance mmWave AlGaN/GaN HEMTs on 6-inch silicon substrates. Under 28 GHz pulsed wave testing conditions, our devices have exhibited a saturated output power of 5.61 W/mm with a power added efficiency(PAE) of 40.2%.

The cross-sectional structure of the device is shown in Figure 1(a). Device fabrication begins with Ar ion implantation for isolation. Subsequently, Ti/Al/Ni/Au (20/120/40/50 nm) is evaporated and annealed for 30 s at 780 °C in N_2 atmosphere to form ohmic contacts. Surface passivation with a 120 nm SiN_x layer is achieved using a PECVD system to support the T-gate. The 150 nm T-gate is prepared by electron-beam lithography and SiN_x etching. The gate metallization consists of Ni/Au (50/400 nm). Figure 1(b) shows the detailed structure of the 150 nm T-gate. After the front-side process is completed, the wafer is temporarily bonded to a 150 mm sapphire substrate. The wafer is then thinned to 100 μm. Subsequently, The gallium nitride and silicon in the specific areas are removed to form vias. Followed by electroplating of 5 μm gold to complete the backside metallization. Finally, the temporarily bonded sapphire wafer is debonded.

Figure 2 shows the DC characteristics of the 150 nm GaN HEMT with a gate width of $W_g = 2\times50$ μm, the device achieves a peak transconductance of 402 mS/mm, and a maximum drain saturation current of I_{dsat} = 1.2 A/mm. Under the bias condition of V_g = -3.1 V, the small-signal characteristics are shown in Figure 2(c). After de-embedding the test pads, the device exhibits cutoff frequencies of f_T/f_{max} = 55/74 GHz. Figure 3 illustrates the large-signal characteristics of the device, we conducted the test under 28 GHz pulsed wave conditions, the device demonstrates a linear gain of 8.5 dB, a saturated output power of 5.6 W/mm, and a peak PAE of 40.2%.

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ED-Tue-P36* - Thermal generation rate of hole traps in GaN MOS structures

4. Electronic devices

Masahiro Hara[1]
Kenji Hirahara[1], Mikito Nozaki[1], Takuma Kobayashi[1], Heiji Watanabe[1]
[1] The University of Osaka, Suita, Osaka 565-0871, Japan

Abstract text: Reduction of hole traps in GaN MOS structures is crucial for improving the reliability of GaN vertical MOSFETs. We have recently reported that a defect thermally induced in a gallium oxide (GaO*x*) interlayer, which is formed during the gate dielectric deposition and post-deposition annealing (PDA), is a major origin of the hole trap. For a deeper understanding of the thermal generation of the hole trap, in this study, we tried to characterize the generation rate of the hole trap with SiO_2/p-GaN MOS capacitors fabricated by systematically varying the PDA temperature and duration.

The starting material was a p-type GaN epitaxial layer (~10^{17} cm^{-3}). After wet cleaning, activation annealing was performed at 800°C in N_2. The samples were wet-cleaned again, followed by the deposition of about 30 nm-thick SiO_2 via PECVD (substrate temperature: 400°C). Then, PDA in O_2 ambient was performed with various PDA durations (1–60 min). The PDA temperature was selected as 300–600°C to minimize the GaO*x* growth by PDA and to investigate the effect of PDA temperature and duration on the hole trap generation in the pre-existing GaO_x interlayer. Finally, Ni gate and Al backside electrodes were deposited to fabricate MOS capacitors.

In the capacitance-voltage (*C*-*V*) characteristics of the 300°C-annealed samples, hole accumulation was observed with the maximum capacitance almost identical to the oxide capacitance, regardless of the PDA duration. On the other hand, at the PDA temperature of 600°C, a large hump was found in the *C*-*V* characteristics due to severe surface potential pinning even after a very short period of PDA (<1 min), and hole accumulation was hardly observed. Then, the hole trap density (N_{hump}) was quantified by analyzing the voltage range of the hump in the *C*-*V* curves. It turned out that N_{hump} was strongly dependent on the PDA temperature but independent of the PDA duration, that is, thermally induced hole traps were generated in a very short time and the density was almost uniquely determined by the PDA temperature and the thickness of the pre-existing GaO*x* interlayer.

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ED-Tue-P37* - A Highly Linear 2-Transistor Monolithic Temperature Sensor Employing p-GaN HEMTs for GaN Power ICs

4. Electronic devices

Fangqing Li[1]
Xinyu Sun[1], Yifan Dong[1], Haodong Wang[1], Yaozong Zhong[2], Haoran Qie[2], Hongwei Gao[1], Xin Chen[2], Qian Sun[2], Hui Yang[2]
[1] School of Nano Technology and Nano Bionics, University of Science and Technology of China, Hefei, China
[2] Key Laboratory of Semiconductor Display Materials and Chips, Suzhou Institute of Nano-Tech and Nano- Bionics, Chinese Academy of Sciences, Suzhou, China

Abstract text: This study presents a highly linear, monolithically integrated temperature sensor based on GaN HEMTs, validated through theoretical modeling and experiments. Utilizing a commercial p-GaN platform, the sensor employs only two transistors, making it the most compact GaN monolithic temperature sensor to the authors' knowledge. The sensor integrates multiple thermosensitive mechanisms, including Schottky barrier effects, 2DEG mobility degradation, magnesium doping ionization, and defect dynamics. This yields exceptional linearity ($R^2 > 0.99$) over 25 to 225°C. By transitioning from a depletion/enhancement-mode (D/E-mode) to an E-mode configuration with structural optimization, sensitivity improves 25-fold, from -0.1 to -2.53 mV/°C.

Experimental results show that E-mode HEMTs' superior thermosensitivity arises from multiphysics coupling effects. Under high-voltage gate stress, lattice defects and interface states induced by the Mg-doped p-GaN layer amplify the threshold voltage shifts (ΔV_{TH} = 0.42 V vs. 0.1 V in D-mode) and the temperature coefficients of the drain current (71.42%/100 °C vs. 46.63%/100 °C). A dual compensation mechanism, leveraging the positive temperature coefficient of the Schottky barrier and the negative coefficient of 2DEG mobility, achieves a temperature-insensitive module with a coefficient of 3.24%/100°C under tailored biasing.

The design employs D-mode and E-mode HEMTs as individual temperature-sensitive units with unique configurations, integrated with a temperature-insensitive E-mode module. Exploiting drain-induced barrier lowering (DIBL) and self-heating differences enhances thermosensitivity, yielding sensitivities of -0.10 mV/°C (D/E-mode) and -1.45 mV/°C (E-mode). Optimizing the gate width ratio (β) from 5 to 2 elevates E-mode sensitivity to -2.53 mV/°C with $R^2 = 0.994$, validating the theoretical model and adaptability to thermal monitoring.

Compared to GaN-, SiC-, and Si-based sensors, this solution exhibits competitive linearity and sensitivity. The two-transistor design offers a 7.5-fold sensitivity increase (-2.53 mV/°C vs. -0.35 mV/°C) over previous 17-transistor GaN monolithic implementations. The sensor shows significant potential for real-time temperature monitoring in critical applications such as AI accelerator chips and electric vehicle power modules.

ED-Tue-P38 - Meandering Tapered Gate HEMTs for Improved Thermal Performance

4. Electronic devices

Shahed Reza[1]
Maher Salloum[1], Brianna Klein[1], **Andrew Binder**[1]
[1] Sandia National Laboratories, Albuquerque, New Mexico, USA

Abstract text: Reliability degradation due to heating is a critical issue for high-power device technologies such as Aluminum Gallium Nitride/Gallium Nitride (AlGaN/GaN) High Electron Mobility Transistors (HEMTs). This issue is complicated by heat conductivity degradation at higher temperatures and non-uniform temperature distribution across the device area. Increasing the device area to manage temperature is not attractive due to lower power density, increased size, and wafer cost. We present a novel tapered meandering gate topology that lowers and improves the uniformity of the operating temperature by distributing heat more evenly over the device area.

In a GaN HEMT, heat is dissipated along a narrow region near the drain side of the gate, with the maximum temperature located at the center region of the device. Thermal simulation results demonstrate that this design can provide substantial temperature reductions compared to the conventional straight finger design by moving the heat-dissipating channels away from the center of the device, offering an additional degree of flexibility in thermal management.

Increasing the spacing between adjacent gates or segmenting the channel to distribute heat sources would lower the channel temperature but would also increase device area, wafer cost, and reduce power density. We present thermal simulation results of the meandering gate topology, which allows for moving heating elements away from the center.

3D models for conventional straight gate and meandering gate devices were developed, and thermal simulations were performed in COMSOL®. The meandering gate packs more periphery compared to a straight gate, achieving the same total periphery with fewer gates. The meandering designs can substantially reduce maximum device temperature and improve temperature uniformity. The maximum temperature improvement of the 6-finger tapered meandering design is 7.4°C compared to the conventional 8×100 μm HEMT with the same area, periphery, and power dissipation. An additional 7.2°C improvement was achieved with mirrored designs, translating to approximate total of 3× operating life improvements based on the rule of thumb of 2× life increase per 10°C change. This topology is generic and can be applied to other high-power device technologies.

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ED-Tue-P39* - Temperature-Dependent Analysis of Enhancement-Mode P-Channel Recessed-MOS GaN FETs

4. Electronic devices

Seung-Su Kim[1]
Ho-Young Cha[1]
[1] School of Electronic and Electrical Engineering, Hongik University, Seoul, Korea

Abstract text: GaN is attracting attention for high-efficiency power switching applications. A recent trend in technology development is the integration of monolithic GaN ICs with power switching devices. So far, GaN ICs have been composed exclusively of N-channel FETs due to the absence of a mature GaN CMOS technology. A p-channel GaN FET is essential for CMOS implementation. In this study, we developed a fabrication process for an enhancement-mode p-channel GaN FET, applying a recessed MOS-gate structure to a p-GaN/AlGaN/GaN heterostructure. This design is compatible with monolithic integration with N-channel FETs, E-mode GaN power devices, and other passive components. The p-GaN layer was 100 nm thick, with the gate region etched by 85 nm. The fabricated p-channel FET exhibited enhancement-mode operation with a threshold voltage of -0.95 V at 1 μA/mm. The maximum drain current and transconductance were 1.84 mA/mm and 1.276 mS/mm respectively, at a gate voltage of -6 V. The source-to-gate (L_{sg}) and gate-to-drain (L_{gd}) distances were both 4 μm, while the recessed MOS region (L_g) was 2 μm long. Temperature-dependent current-voltage characteristics were investigated from room temperature to 200°C, revealing that the on-resistance changed by only 10% at a drain voltage of -2 V. Our analysis showed that the contact and parasitic resistances of the source-to-gate and gate-to-drain regions decreased, whereas the recessed-MOS channel resistance increased. The reduction in contact resistance at elevated temperatures was attributed to the decreased effective barrier height of the non-ideal p-type ohmic contact. The decreased parasitic resistances resulted from an increased ionized hole concentration. Although hole mobility decreased with rising temperature, the increase in ionized hole concentration played a more dominant role in reducing resistance. In contrast, the increase in MOS-channel resistance was due to enhanced scattering at elevated temperatures. These findings are crucial for designing p-channel FETs, where temperature-dependent characteristics are influenced by differing behaviors in the MOS channel and parasitic regions. The overall temperature characteristics depend on L_{sg}, L_g, L_{gd}, and contact resistance. A detailed analysis will be presented at the conference, along with a demonstration of CMOS integration with N-channel FETs.

ED-Tue-P40 - High-Temperature Characteristics of Extreme Bandgap MOSHFET

4. Electronic devices

Abdullah Al Mamun Mazumder[1]
Abdullah Mamun[2], Tariq Jamil[1], Grigory Simin[1], Asif Khan[1]
[1] University of South Carolina
[2] Advanced Semiconductor Materials America Inc.

Abstract text: Extreme Bandgap (EBG) semiconductors based on $Al_xGa_{1-x}N$ ($x > 0.6$) pave the way to the next step in performance improvement of power electronics. EBG devices with even higher bandgap can potentially outperform GaN and SiC devices in many power and radiofrequency applications especially under severe conditions like high ambient temperatures. This paper presents the characteristics of EBG AlGaN-channel Metal-Oxide-Semiconductor Heterostructure FET (MOSHFET), in the temperature range of 0ºC to +300ºC.

The structure from bottom to top is as follows: 2.6 μm thick AlN buffer on sapphire/ 140 nm i-$Al_{0.87}Ga_{0.13}N$/ 100 nm i-$Al_{0.64}Ga_{0.36}N$ channel/ 23 nm n-$Al_{0.87}Ga_{0.13}N$ barrier/ and 30nm $Al_xGa_{1-x}N$ (x= 0.87 to 0.40). A 150/1000/400/300 Å Zr/Al/Mo/Au metal stack was deposited utilizing an e-beam for source/drain connections, followed by 950 °C thermal annealing for 30s in N_2. Slow-etch ICP-RIE was used to etch the reverse-graded layer from the access region and 10 nm of the barrier layer under the gate from half the sample to make the recessed structure and half of the remaining plain gate. Atomic layer deposition was used to produce a 25-nm ZrO_2-Al_2O_3 oxide stack in the access area of both types of devices before constructing the Ni/Au gates. Plasma-enhanced chemical vapor deposition was used to deposit a 250-nm Si_3N_4 layer. Gate length, source, and drain spacings were: L_G = 1.8 μm, L_{SG} = 1.7 μm, and L_{GD} = 2.5 μm.

At room-temperature we measured the contact resistance R_c = 3.6 Ohm-mm and the sheet resistance R_{sh} = 3200 Ohm/sq. At 300°C these parameters increase 2.4 and 2.2 times respectively, due to reduced electron mobility. For a temperature rise from 25 ^{0}C to 300^0 C, for the plane gate structure the peak drain current I_{DS} at V_g = +6V, decreases by 30% from 274 mA/mm to 191 mA/mm. For the recess gate structure, I_{DS} decreases only by 15% from 222 mA/mm to 189 mA/mm. These results suggest that the recess gate design provides better thermal stability. Noticeably, at temperatures above 200°C, drain currents for recessed and plain gate devices are nearly the same. The reason for this is that at high temperature an increased access resistance (both R_c and R_{sh}) become a dominating limiting factor for I_{DS}. Temperature-dependent threshold voltages show a maximum of 1.4 V shift toward zero for plain gate and 1.1 V shift toward more negative values for recessed gate structure.

ED-Tue-P41* - Impact of Prolonged, High Temperature Exposure on AlGaN/GaN Heterostructure at 500C up to 216 Hours

4. Electronic devices

Can Jiang[1]
John Niroula[1], Tomás Palacios[1]
[1] Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract text: High-temperature electronics (≥500°C) are critical for applications such as Venus exploration and geothermal energy extraction. Geothermal energy, a promising renewable resource, is underutilized due to the lack of durable electrical devices that withstand extreme temperatures. Traditional silicon-based devices fail beyond 250°C, while wide-bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) excel in these conditions due to their wide-bandgap and negligible carrier thermal generation.

While SiC reliability has been demonstrated, few studies examine AlGaN/GaN heterostructures above 300°C long-term [1-4]. This work investigates transfer length method (TLM) structures on GaN, both unpassivated and passivated with SiN or SiO_2, exposed to 500°C in air for 216 h. Electrical measurements at room temperature tracked sheet and contact resistance over time. To the authors' knowledge, this is the longest high-temperature duration study on AlGaN/GaN heterostructures. The unpassivated TLM structures retained their electrical properties for 144 h before significant degradation, whereas 100 nm SiO2/SiN-passivated samples remained stable beyond 216 h.

Post-degradation analysis via scanning electron microscopy and atomic force microscopy revealed a 50x surface roughness increase in the unpassivated sample, consistent with the mechanisms reported in the literature that the AlGaN surface reacts with the high temperature, leading to microcracks. Furthermore, the SiN/SiO2 passivated dielectric layer resulted in a stable heterostructure that retains its sheet resistance beyond 216 h. These results advance understanding of high-temperature GaN-based electronics degradation and demonstrate passivation as an effective mitigation strategy.

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ED-Tue-P42* - 30°C Junction Temperature Reduction @ 24 W/mm in GaN Devices Enabled by 300 nm Polycrystalline Diamond Heat Spreader with AlN Insertion Layer

4. Electronic devices

Kexin Deng[1]
Xinhua Wang[1], Sen Huang[1], Qimeng Jiang[1], Ke Wei[1], Yingkui Zheng[1], Xinyu Liu[1]
[1] Institute of Microelectronics of Chinese Academy of Sciences

Abstract text: Self-heating in GaN power devices limits reliability at high power densities. Though diamond's extreme thermal conductivity (2000 W/m·K) offers a solution, direct GaN/diamond integration suffers from: (1) interfacial delamination from thermal mismatch stress, (2) hydrogen plasma etching damage during diamond deposition, and (3) carbon interdiffusion at elevated temperatures.

We report a thermally efficient GaN/AlN/polycrystalline diamond architecture enabled by a AlN interlayer. The 10-nm AlN layer (1) buffers thermal stress via controlled nanocrystalline morphology, (2) provides nucleation sites for growing 300 nm diamond films through microwave plasma CVD, and (3) Plasma/diffusion barrier blocking H-induced GaN etching and C interdiffusion. Sequential dry etching protocols overcome diamond's hardness and anisotropic etching behavior, achieving damage-free mesa formation. The diamond-first integration strategy avoids post-growth induced interface degradation.

The heterostructure achieves ultra-low thermal boundary resistance of 6.5 $m^2 \cdot K/GW$. At 24 W/mm operation, transient thermal analysis shows peak junction temperatures reduced by 30°C versus conventional SiN-passivated references. TEM/EDS confirms abrupt interfaces without interdiffusion. This integration methodology resolves long-standing thermal and process bottlenecks for diamond-enhanced GaN electronics.

ED-Tue-P43* - Study on Gate with Ferroelectric Multilayers by Annealing Treatments on the Performance of GaN MOS-HEMTs Grown on SiC substrate

4. Electronic devices
Po Chuan Liao[1]
Ray Hua Horng[1]
[1] Institute of Electronics, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan, R.O.C.

Abstract text: GaN metal-oxide-semiconductor high electron mobility transistors (MOS-HEMTs) fabricated on SiC substrates are promising for high-power and high-frequency applications due to their superior thermal conductivity, high breakdown voltage, and excellent carrier mobility. To achieve enhancement-mode (E-Mode) operation, Al_2O_3-HZO-Al_2O_3 ferroelectric charge trap gate stacks were employed, with the integration of an HfON charge trap layer for enhanced charge stabilization and polarization alignment.

This study systematically compared the effects of post-deposition annealing (PDA) and post-metallization annealing (PMA) on device performance. PMA-treated devices exhibited superior electrical properties, including a higher threshold voltage (V_{th}) of 4.51 V at V_{DS} = 10 V, reduced subthreshold swing (SS), and improved On/Off current ratios. These improvements are attributed to enhanced ferroelectric polarization, reduced interface trap densities, and the charge trapping efficiency of the HfON layer, which significantly reduced leakage currents and stabilized polarization.

The initialization process, applied to align ferroelectric polarization, further amplified the positive Vth shifts and improved operational stability. Devices with thicker ferroelectric stacks exhibited greater V_{th} shifts, reaching a maximum of 5.39 V, underscoring the combined benefits of initialization and HfON integration. C-V measurements highlighted that PMA-treated devices achieved sharper polarization transitions and lower dispersion effects, indicating superior ferroelectric layer crystallization and reduced defect densities compared to PDA-treated devices.

In contrast, PDA-treated devices exhibited broader C-V transitions and incomplete crystallization of the HZO layer, resulting in relatively poorer performance. This study demonstrates the critical role of PMA in improving ferroelectric stack crystallinity and electrical characteristics, enabling reliable and efficient E-Mode operation.

These findings highlight the importance of annealing treatments, material optimization, and polarization alignment processes in advancing GaN MOS-HEMT technology for applications such as electric vehicles, renewable energy systems, and industrial power supplies. The integration of HfON within the ferroelectric gate stack offers a scalable pathway to achieving stable and high-performing devices.

ED-Tue-P44 - Effect of sharp interface on 2-DEG characteristics of AlGaN/GaN HEMTs regrown on high quality AlN buffer layers

4. Electronic devices

Chuyoung Cho[1]
Young-Hun Han[2], Jiseon Lee[1], Jeong-Gil Kim[3], Yumin Koh[1], Dong-Hyun Kim[1], Keun-Man Song[1], June-O Song[2]
[1] Korea Advanced Nano fab Center, Suwon, Republic of Korea
[2] WaveLord Inc., Hwaseong, Republic of Korea
[3] Dong-A University, Busan, Republic of Korea

Abstract text: Recently, AlN buffer layers have been actively studied as an alternative to GaN buffer layers to suppress the trapping effect in the buffer layers of AlGaN/GaN high electron mobility transistor (HEMT). Since AlN has a large band offset and high polarization field, it is possible to confine up to two-dimensional electron gas (2-DEG) in the channel. In addition, the very large band gap energy of 6.2 eV of the AlN layer can provide inherent high-resistivity nature of the layer without doping deep acceptor traps such as Fe or C ions used in conventional GaN buffer layers. In this study, we have demonstrated AlGaN/GaN HEMT regrown on the high quality AlN buffer layer with superior interface and investigated the AlN thickness-dependent growth mechanism.

The high quality AlN buffer layer was grown on 4 inch semi-insulating SiC substrate by high-temperature metal–organic chemical vapor deposition at the growth temperature of 1,350 ℃. Then the AlGaN/GaN heterostructures were regrown on high quality AlN layers and fabricated the devices. In order to get the superior 2-DEG properties, regrown epitaxial layer composing the AlGaN/GaN heterostructure was systematically optimized through the several analysis methods and device fabrication. The regrown epitaxial quality was estimated by the X-ray diffraction (002)/(102) rocking curve of 208 and 369 arcsec, respectively. Transmission electron microscopy analysis revealed that sharp interface and good crystalline quality are realized by controlling the various growth parameters. A high 2-DEG mobility of 2,200 $cm^2/V{\cdot}s$ and the 2-DEG density of 1.01×10^{13} cm^{-2} were achieved with a high degree of uniformity throughout the 4-inch wafer and a good channel controllability was confirmed. These results suggested that the AlGaN/GaN HEMT regrown on AlN with high crystalline quality was successfully demonstrated and could be used for high performance RF and power applications. In the presentation, we will describe the recent progress in the AlGaN/GaN HEMT regrown on AlN buffer layer.

ED-Tue-P45* - TCAD Analysis of the Impact of Impurities and Traps in the AlGaN Barrier of GaN HEMTs on the CV Characteristics of MIS Structures

4. Electronic devices

Kosuke Miura[1]
Takeshi Suwa[1], Ryohei Nega[1]
[1] Komukai-Toshiba-cho, Saiwai-ku, Kawasaki, Japan

Abstract text: GaN HEMTs are devices that utilize the two-dimensional electron gas (2DEG) formed at the AlGaN/GaN interface as a channel. Since impurities and traps within the AlGaN barrier significantly impact the 2DEG, thereby affecting device characteristics and reliability, modeling these elements is essential for technology CAD (TCAD) simulations. In the MIS (Metal-Insulator-Semiconductor) structure, as shown in Fig. 1, which includes a gate and drain contacts and silicon nitride (SiN) as the insulating film, the capacitance-voltage (CV) characteristics between the gate and drain exhibit hysteresis and plateaus. These features reflect the characteristics of impurities and traps in the AlGaN barrier. Using a TCAD model calibrated to CV characteristics of MIS sample with impurities, we analyze the impact of traps on CV characteristics.

In this report, we present the results of reproducing the CV characteristics of an MIS sample with impurities using TCAD simulation and analyzing the impact of impurities and traps in the AlGaN barrier. Some samples have a maximum capacitance value lower than the theoretical value, which is presumed to be caused by the silicon detected by Secondary Ion Mass Spectrometry (SIMS). Therefore, we set the impurities and traps in the AlGaN barrier based on SIMS analysis and the hysteresis in the CV waveform. We divided the AlGaN barrier into simple four layers to set the impurity distribution based on SIMS analysis in our TCAD simulation. as shown in Fig. 2. The impurity levels were set uniformly within each layer. Fig. 3 compares the measured and simulated CV characteristics. The measured data shows different hysteresis magnitudes between the first and second cycles of gate voltage. By setting two types of electron traps with different levels and one type of hole trap near the SiN/AlGaN interface in the TCAD model, we were able to reproduce this behavior. Additionally, mechanism analysis using TCAD revealed that the band bending caused by silicon and hydrogen resulted in the formation of regions with high electron concentration in the AlGaN barrier, increasing the effective thickness and reducing the capacitance. By using the TCAD model with impurities in the AlGaN barrier based on SIMS and traps based on the hysteresis magnitudes in the CV waveform, we clarify the impact of impurities and traps in the AlGaN barrier on the CV characteristics.

ED-Tue-P46* - The Two Dimensional Hole Gas in Hexagonal Boron Nitride Grown on (100) Silicon Substrates by Metal Organic Chemical Vapor Deposition

4. Electronic devices

Chen-Da Du[1]
Yu-Hua Hsu[1], Yi-Yue Chiang[1], Yun-Chorng Chang[2], Kun-Yu Lai[1]
[1] Department of Optics and Photonics, National Central University, Taoyuan 320, Taiwan (R.O.C)
[2] Research Center for Applied Sciences, Academia Sinica, Taipei 11529, Taiwan (R.O.C)

Abstract text: In this study, hexagonal boron nitride (hBN) was epitaxially grown on high-resistance (100) silicon substrates using metal-organic chemical vapor deposition (MOCVD). The epitaxial process was conducted through a pulsed-flow growth method, and the transformation from turbostratic boron nitride (tBN) to hBN was observed via transmission electron microscopy (TEM) and X-ray absorption spectroscopy (XAS)[1][2].

Temperature-dependent Hall effect measurements revealed the formation of a high-concentration hole channel at the hBN/Si heterointerface, with a hole density of 1.2×10^{15} cm^{-2} and a mobility of 51 $cm^2/V\cdot s$ at room temperature. Low-temperature Hall measurements conducted at 13 K still exhibited a stable hole density of 1.5×10^{15} cm^{-2} and a mobility of 47 $cm^2/V\cdot s$, showing excellent temperature stability of the two dimensional hole gas (2DHG).

Band structure simulations indicated significant hole accumulation at the hBN/Si interface. The large band offset effectively suppressed interface scattering, providing superior carrier confinement. Additionally, compared to those created by the conventional GaN/AlN heterostructures, the hole channel at the BN/Si interface is wider, highlighting the potential of hBN for carrier modulation applications in heterostructure devices.

ED-Tue-P47 - Enhancement of Electromechanical Coupling Coefficient in AlN/Si BAW filters by Ti-ion Implantation

4. Electronic devices

Manoj Prabhakar Mohan[1]
Arokiaswami Alphones[1], **Subramaniam Arulkumaran**[2], Maung Ye Kyaw Thu[2], Ng Geok Ing[1], Holger Fiedler[3], John Kennedy[3]
[1] School EEE, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798
[2] Temasek Laboratories@NTU, Nanyang Technological University, Research Techno Plaza, 50 Nanyang Drive, Singapore 637553
[3] National Isotope Centre, GNS Science, Lower Hutt 5010, New Zealand

Abstract text: Recently, high frequency filters for 5G and 6G applications have been realized using single crystalline piezoelectric materials like AlN, AlGaN, ScAlN, SiC, Ga_2O_3, Diamond and etc... Thin Film Bulk Acoustic Wave Resonators (FBAR) with epitaxially grown, single crystalline piezoelectric material have shown performance improvements like improved acoustic velocity, potentially improved piezoelectric coefficient, and improved thermal conductivity compared with resonators based on polycrystalline piezoelectric material. A suspended epitaxial AlN FBAR with piezoelectric coupling coefficient, K^2 of 7.8% at 12 GHz is demonstrated in this work. By introducing external stress with ion implantation, the piezoelectric properties are changed thereby increasing the K^2 of the AlN FBAR. Single crystalline AlN was grown on 100-mm diameter Si (111) substrate by MOCVD system.

The fabrication process starts with the formation of 12umx50um opening using photolithography process followed by 30keV Ti ion implantation at room temperature with a fluence of 1E+15/cm^2. A selective implantation was performed using the photoresist mask. After the interconnect metallization, the AlN/Si wafer went through back-grinding process to reduce the Si substrate thickness down to 150um. Then, the deep trench etching was done using Deep Reactive Ion Etching system with Ni hard-mask. Finally, the Bottom Electrode was formed by sputtering of Ti/Au followed by gold plating to have a good metal coverage in the formed trenches.

The FBAR with and without implantation are tested using the probe station. The measured S-parameters were converted to Z-parameters and the K^2 were extracted using the formula $K^2 = (\pi f_s/2f_p)\cot(\pi f_s/2f_p)$, where f_s and f_p are series and parallel resonance frequencies of FBAR. The f_s and f_p are extracted from local minimum and the local maximum of the bands respectively. For the implanted case, the f_s is at 11.53GHz and f_p is at 11.92GHz whereas the f_s and f_p for the un-implanted case are at 11.72GHz and 11.92GHz, respectively. The measured K^2 is 4.07% from the un-implanted AlN/Si FBAR. However, the K^2 of implanted AlN/Si FBAR is 7.8% which is ~1.9-times higher than the un-implanted AlN/Si FBAR. The enhancement of K^2 is mainly due to the increase of piezoelectric modulus of AlN by Ti ion implantation. The details of the measured results will be discussed at the conference.

ED-Tue-P48* - Impurity and Distributed Polarization Doping for AlN-Based Schottky Barrier Diodes

4. Electronic devices

Christoph Margenfeld[1]
Karl Kreuzer[1], Samuel Faber[2], Jana Hartmann[1], Bernd Witzigmann[2], Andreas Waag[1]
[1] Nitride Technology Center, Institute of Semiconductor Technology, Technische Universität Braunschweig, Braunschweig, Germany
[2] Institute of Optoelectronics, Friedrich-Alexander University Erlangen-Nuremberg, Erlangen, Germany

Abstract text: Ultra-wide bandgap (UWBG) semiconductors are very attractive for power switching applications, such as charging infrastructure for electric vehicles in the 800 V class. Since the critical field is scaling super-linearly with band gap energy, UWBG semiconductors are favorable materials for power devices, as high breakdown voltages may be achieved at lower drift layer thicknesses. This in principle enables devices with high voltage blocking capabilities at reduced specific on-resistances. However, the potential of UWBG materials can only be capitalized on if doping can be controlled reliably. Currently, impurity doping of AlN and high aluminum content AlGaN remains lackluster. Thus, distributed polarization doping (DPD) is seen as a promising alternative to achieve efficient doping in the AlGaN material system.

We manufactured quasi-vertical Schottky barrier diodes (SBDs) with either AlN:Si or graded $Al_{0.8}Ga_{0.2}N \rightarrow AlN$ drift layers and $Al_{0.8}Ga_{0.2}N$:Si bottom contact layers on cost-efficient, low-defect high-temperature annealed AlN/sapphire templates. Capacitance-voltage measurements on the SBDs with AlN:Si drift layer yield a net donor concentration of $2 \cdot 10^{17}$ cm^{-3} at a nominal doping level of $1 \cdot 10^{18}$ cm^{-3}, from which a room-temperature free electron concentration in the low 10^{15} cm^{-3} range is estimated. Despite the carrier density being one order of magnitude below desirable values, SBDs with reasonable properties could be manufactured. We obtain turn-on voltages of 2.0 V with a Cr Schottky electrode and differential on-resistances below 40 mΩ cm^2. The devices provide a rectification ratio of 10^6 at ±12 V and current handling capability of 600 mA (90 A/cm^2) at 12 V.

When employing distributed polarization doping with an aluminum concentration difference of $\Delta x = 0.2$, the maximum achievable drift layer thickness is limited by the background acceptor density in high aluminum content AlGaN, which is assumed to be mainly due to carbon incorporation from the metalorganic precursors. At conditions favorable for heavy n-doping, the acceptor background may be as high as some 10^{17} cm^{-3}, limiting the DPD layer thickness to values below ~800 nm. We employ MOVPE growth processes tailored to low carbon incorporation and evaluate the feasibility of DPD for power devices requiring thick drift layers with controllable doping.

ED-Tue-P49* - Study of Distributed Polarization Doped (DPD) Extreme Bandgap AlGaN Layers for Devices

4. Electronic devices

Tariq Jamil[1]
Abdullah Al Mamun Mazumder[1], Mafruda Rahman[1], Muhammad Ali[1], Grigory Simin[1], Asif Khan[1]
[1] Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208, USA

Abstract text: Extreme bandgap (EBG) $Al_xGa_{1-x}N$ ($x > 0.6$) DPD epilayers are key to overcoming the conductivity challenges posed by high Al-composition $Al_xGa_{1-x}N$ layers. They provide a pathway to electron and hole conduction to the AlN active layers for electronic and optoelectronic devices. In this work, we show that the EBG $Al_xGa_{1-x}N$ ($0.7<x<1$) DPD layers can themselves serve as the active layers for high performance quasi-vertical conduction devices.

For our study, 400 nm thick un-doped linearly graded layer $Al_{0.70-1}Ga_{0.30-0}N$ DPD layers were grown over 800 nm thick highly doped n^{++}-$Al_{0.7}Ga_{0.3}N$ *n*-contact layer over bulk AlN substrates using low-pressure MOCVD. The doping of n^{++}-$Al_{0.7}Ga_{0.3}N$ was measured to be ~1 x 10^{19} cm^{-3}. The root-mean-square (RMS) surface roughness of the active DPD layer was 0.2 nm for a 5×5 μm area scan. Its doping as determined from CV was 1 x 10^{17} cm^{-3} and grading linearity from 0.7 to 1 was confirmed by the SIMS and X-ray. The RSLM confirmed our structure to be nearly pseudomorphic.

Then 30 µm diameter circular MESA geometry quasi-vertical conduction Schottky barrier diodes were fabricated. ICP etching was used to access the n-contact formation n^{++}-$Al_{0.7}Ga_{0.3}N$ layer. Zr/Al/Mo/Au (15/10/40/30 nm) metallization was used for the n-contact metals with a subsequent 950 ºC anneal in N_2 for 30 sec. Schottky Ni/Au contacts were then deposited on top of the graded composition DPD layer.

An ideality factor η = 1.3 and specific on-resistances R_{ON-SP} < 0.5 mΩ-cm^2 have been extracted from the Schottky diode I-V characteristics. From a linear scale forward I-V, we measured the turn-on voltage to be approximately 2.2 volts. The forward current density was measured to be >14 kA/cm^2 at 15 V. The breakdown voltage was approximately 170-200 V that translates to approximately 4-5 MV/cm. It is important to note that the breakdown was measured without passivation and field-plating etc. We believe that it can be increased with passivation and field plating. In addition, to the Schottky diode on n-DPD layers, we will also present our initial results on EBG AlGaN p-DPD layers' characterization.

ED-Tue-P50 - Ferroelectricity-driven inhomogeneity and giant nonlocality in Graphene/twisted WSe2 heterostructure

4. Electronic devices
Rahul Debnath[1]
[1] IISc Bangalore

Abstract text: The artificial moiré superlattices have extended our design space by allowing two atomically thin layers to be rotated at a desired twist angle to form a moiré pattern that modifies the electronic band structure of the system. Unlike twisted bilayer graphene, where the flat bands occur only near the magic angle of 1.1^0 due to delicate competition between the hybridization energy and the kinetic energy; twisted bilayer TMDC offers a range of twist angles, where the hybridization energy and the highly commensurate domains are varied with the moiré wavelength. However, unlike graphene, TMDC materials show a massive contact resistance. To overcome this issue, we used graphene as a sensing layer to probe the electronic effects of the underlying twisted TMDC structure on monolayer graphene. Here, we report the observation resistance features on either side of the graphene's Dirac point, which can be tuned further by applying a transverse electric field. The appearance of multiple resistance peaks can be explained by the coexistence of the MX/XM domains of twisted WSe_2 having opposite polarization that can be filliped by applying a vertical electric field, which indicates the likely signature of ferroelectricity. We quantitatively characterize the hysteretic ferroelectric gating (coming from the twisted WSe_2 between the bottom gate and the graphene) using the reference of an independent background doping (hBN Top gate) provided by normal dielectric gating. We also observe the electric field tunability of the nonlocal resistance, which cannot be explained by the classical ohmic contribution. In our device, due to the proximity of graphene to the ferroelectric twisted WSe_2, non-zero Berry Curvature could emerge in graphene by breaking the inversion symmetry of the lattice globally. We further explore the magnetotransport properties of the system and find that the magnetoresistance of the sample increases with an in-plane magnetic field. Our device design not only combines the individual characteristics of the 2D materials but also opens up a new possibility to study the exotic physical properties absent in the parent compounds.

ED-Tue-P51 - AlScN/GaN (MIS)HEMTs grown by Metal-Organic Chemical Vapor Deposition

4. Electronic devices

Alexander Schmid[1]
Peter D. B. Fischer[1], **Franziska C. Beyer**[2], Ali Yassine[3], Isabel Streicher[4], Teresa Duarte[5], Stefano Leone[5], Oliver Ambacher[3], Johannes Heitmann[1]
[1] TU Bergakademie Freiberg, Institute of Applied Physics, Freiberg, Germany
[2] Fraunhofer Institute for Integrated Systems and Device Technology, Freiberg, Germany
[3] University of Freiburg, Department of Sustainable Systems Engineering, Freiburg, Germany
[4] Consiglio Nazionale delle Ricerche - Istituto per la Microelettronica e Microsistemi (CNR-IMM), Catania, Italy
[5] Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Abstract text: AlScN/GaN heterostructures are a promising material system for high electron mobility transistors (HEMTs). The large polarization charge enables a high sheet carrier density n_s of up to $5 \cdot 10^{13}$ cm^{-2} in the two-dimensional electron gas (2DEG) at the AlScN/GaN interface [1]. Compared to $Al_{0.25}Ga_{0.75}N$/GaN heterostructures this is an increase by a factor of five which could lead to a reduced on-state resistance of the devices [2]. However, the high AlN-content, which is typically above 80%, leads to a large contact resistance R_C [3]. Additionally, the growth by molecular beam epitaxy (MBE) [4] limits the scalability due to high cost, low growth rate and small sample size.

This work focuses on the fabrication and electrical characterization of (MIS)HEMTs grown by a metal-organic chemical vapor deposition (MOCVD) [5]. Two different heterostructures were prepared on 4" sapphire substrates. The barrier consists of a 10 nm thick $Al_{0.89}Sc_{0.11}N$ layer grown on a thin AlN interlayer. The GaN buffer layer had a thickness of ~2 µm. During growth, sample A was in-situ capped with a 15.5 nm thick SiN layer, while sample B had a 3 nm GaN capping layer. (Ti/Zr)/Al/Ni/Au stacks annealed at 900°C were used as ohmic contacts. A wet chemical treatment was used to micropattern the contact area before metal deposition and hence reduce R_C. Additionally, the SiN cap was removed beneath the gate contact to compare MISHEMT and HEMT devices with the same heterostructure. The HEMT devices showed a saturation current $I_{d,sat}$ of up to 400 mA/mm for devices with 15 µm channel length. The $I_{d,on}/I_{d,off}$ ratio was close to 8 orders of magnitude, indicating the high structural quality of the barrier and low gate leakage current. Two main limitations were found, the still comparable large contact resistance of 1.4 Ωmm and the increase of the sheet resistance R_{sh} from 283 Ω/sq to 581Ω/sq during device processing. The smallest R_{sh} degradation was observed with SiN capping, which protects the barrier from decomposition and oxidation during contact anneal.

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[3] S. Krause et al., *IEEE Electron Device Lett.* 44 (1), 17-20 (2023)

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[5] I. Streicher et al., *Phys. Status Solidi RRL* 17(2), 2200387 (2023)

ED-Tue-P52* - Impact of Atomic Layer Etching Depth on Carrier Mobility in AlGaN GaN HEMTs A Study of Scattering Mechanisms and Optimization

4. Electronic devices

Boxuan Gao[1]
Jiejie Zhu[1], Mengdi Li[1], Lingjie Qin[1], Simei Huang[1], Huilin Li[1], Wanshuo Liao[1], Yuchen Qian[1], Xiaohua Ma[1]
[1] National Engineering Research Center of Wide Band-gap Semiconductor, School of Microelectronics, Xidian University, Xi'an 710071, China

Abstract text: Atomic Layer Etching (ALE) offers an innovative approach to address the limitations of conventional plasma etching techniques. By utilizing its self-limiting mechanism, ALE achieves atomic-scale precision, effectively minimizing surface damage and significantly improving the performance of GaN-based High Electron Mobility Transistors (HEMTs).

In this study, two AlGaN/GaN recessed-gate HEMTs were fabricated using ALE: a depletion-mode HEMT (Sample B) and an enhancement-mode HEMT (Sample C), with an unetched device (Sample A) serving as the control. Post-etching characterization revealed that the root-mean-square (RMS) surface roughness of the recessed region decreased from 0.35 nm to 0.21 nm, demonstrating the efficacy of ALE. Compared to Sample A, the threshold voltage shifted by +2 V and +5 V for Samples B and C, respectively. Although the saturation current density decreased by 7%, the peak transconductance improved by 20% and 40%, underscoring the optimization potential of ALE.

Carrier mobility analysis indicated that Sample B exhibited an increase in mobility from 1310 $cm^2/V \cdot s$ to 1450 $cm^2/V \cdot s$, whereas Sample C experienced a reduction to 522.1 $cm^2/V \cdot s$. The mobility values were derived from DC measurements conducted at temperatures ranging from 300 K to 375 K in 15 K increments, using devices with a gate length of 20 μm at a drain voltage of 0.1 V. MATLAB-based fitting of temperature-dependent trends to theoretical scattering mechanisms revealed optical phonon scattering accuracies of 99.5%, 97.5%, and 23.6% for Samples A, B, and C, respectively. In contrast, the accuracies for remote impurity and interface roughness scattering were 0.35%, 0.97%, and 66.83%, respectively. The reduction in barrier layer thickness led to carrier concentration near the interface, thereby enhancing the dominance of remote impurity and interface roughness scattering, despite the inherently low-damage nature of ALE.

In conclusion, ALE enhances mobility and reduces scattering at optimal etching depths, with optical phonon scattering remaining dominant. However, excessive barrier thinning shifts scattering dominance to remote impurity and interface roughness, degrading mobility. These findings highlight ALE's potential for low-damage etching and GaN HEMT optimization, providing valuable insights for high-performance GaN device design

Coffee break and Poster session 3

2025-07-10
15:00 - 16:00
Coffee break and Poster session 3

GR-Thu-P1* - Capturing ionization energies of acceptors in GaN and AlN with density functional theory

1. Growth
Kelsey Mirrielees[1]
Julianna Davis[1], Douglas Irving[1]
[1] North Carolina State University

Abstract text: Realization of high performance AlGaN based devices, such as LEDs and power electronics, relies on controllable doping to achieve high or low free carrier concentrations. Acceptor-doped AlN, GaN, and AlGaN are of particular interest due to their importance for many next generation devices, as well as the challenges with achieving controllably doped p-type layers. One challenge in achieving desired free hole concentrations is compensation due to the formation of native defects during synthesis or processing. In addition, common p-type dopants such as Mg are known to exhibit higher ionization energies, which have been reported to be ~600 meV in AlN and ~150 meV in GaN. These higher activation energies further limit free carrier concentrations.1 Unintentional impurities introduced during growth as well as dopant-containing defects, including vacancy-complexes that are prevalent in high-doping regimes and interstitials2,3, can further compensate free carriers.

In this work, approaches to capture the ionization energies of acceptors in GaN, AlN, and AlGaN from first principles are explored. The focus is on the Mg acceptor, however insights for the Be acceptor will also be discussed. For the Mg acceptor, it will be shown that using a 96-atom supercell can lead to an overestimation of the Mg ionization energy. This is due to the delocalized nature of the Mg acceptor wavefunction, and the potential for interaction of the wavefunction across periodic boundaries. It will be shown that larger supercells that contain the acceptor wavefunctions produce ionization energies closer to experimental measurements. This will be shown for acceptors in both AlN and GaN, and will be connected back to experimental findings in AlGaN.[1] This material is based upon work supported by the Air Force Office of Scientific Research under award number FA9550-24-1-0269.

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GR-Thu-P2* - Computational Study of Point Defect Formation in InxGa1−xN Thin Films Under MOCVD Growth Conditions

1. Growth

Roman Hrytsak[1]
Pawel Kempisty[1], Ewa Grzanka[2], Malgorzata Sznajder[3], Mike Leszczenski[2]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland
[2] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland
[3] Institute of Physics, University of Rzeszow, Rzeszow, Poland

Abstract text: $In_xGa_{1-x}N$/GaN quantum wells (QWs) are widely utilized in optoelectronic and high-power electronic devices due to their tunable bandgap, making them essential for applications such as light-emitting diodes (LEDs), photodetectors, and high-frequency transistors. However, structural defects, particularly point defects formed during growth, significantly influence material stability and device performance. Predicting defect formation and concentration under various growth conditions is crucial for optimizing the fabrication of $In_xGa_{1-x}N$ heterostructures.

In this study, we employed density functional theory (DFT) calculations to model the formation and thermodynamic stability of point defects in $In_xGa_{1-x}N$ thin films grown using metal-organic chemical vapor deposition (MOCVD). We investigated alloys with indium concentrations of x = 0, 0.11, and 0.22, focusing on neutral and charged gallium vacancies (V_{Ga}) and $In_{Ga}V_{Ga}$ complexes. A computational model was developed to predict the variation in chemical potential and defect concentrations as a function of temperature (0-1000°C) during MOCVD growth. To enhance accuracy, vibrational energy corrections were incorporated into defect formation energy calculations, leading to shifts ranging from 0.6 to 1.25 eV under typical MOCVD conditions. Our results indicate that defect formation energy decreases with increasing temperature, resulting in higher defect concentrations, particularly for charged gallium vacancies.

By providing a predictive model for defect concentrations during MOCVD growth, this study offers valuable insights into the mechanisms governing defect formation in $In_xGa_{1-x}N$ heterostructures. These findings contribute to the optimization of growth conditions to minimize defect-induced degradation, improving the thermal stability and reliability of GaN-based optoelectronic and power devices.

GR-Th-P3* - Diffusion of Magnesium in GaN: Experimental Evidence explained by DFT study

1. Growth

Karol Kawka[1]
Pawel Kempisty[1], Kacper Sierakowski[2], Michal Bockowski[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142, Warsaw, Poland
[2] Department of Materials Science and Engineering at North Carolina State University, Raleigh, NC 27606, United States of America

Abstract text: Gallium nitride (GaN) is a key material in power electronics and optoelectronics, with magnesium (Mg) being the primary acceptor dopant for p-type conductivity. Understanding the diffusion behavior of Mg in GaN is crucial for precise doping control in semiconductor devices.

To investigate the diffusion of Mg in GaN, ion-implanted Mg-doped GaN samples were grown via Halide Vapor Phase Epitaxy (HVPE) and subjected to ultra-high-pressure annealing (UHPA) at temperatures ranging from 1250°C to 1450°C and under nitrogen pressure of 1 GPa. X-ray diffraction (XRD) confirmed the successful removal of implantation-induced damage, while secondary ion mass spectrometry (SIMS) revealed significant diffusion anisotropy. The highest diffusion rates were observed along the [0001] direction, with diffusion coefficients reaching 1.7×10^{-4} cm²/s, approximately an order of magnitude higher than in non-polar directions. The experimental data confirmed vacancy-mediated diffusion as the dominant mechanism.

To better understand Mg diffusion phenomena, density functional theory (DFT) calculations were performed using the SIESTA software within the Generalized Gradient Approximation (GGA) and the Perdew-Burke-Ernzerhof (PBE) exchange-correlation functional. Vacancy-mediated diffusion mechanisms in bulk GaN were examined through Nudged Elastic Band (NEB) calculations, with phonon calculations providing insights into vibrational contributions to migration barriers. The computed diffusion energy barriers, for neutral systems, were 1.26 eV along the [11-20] direction and 1.73 eV along the [0001] direction. The purpose of this work is to expand our knowledge of the behavior of Mg in different charge states and crystallographic directions.

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GR-Thu-P4* - Donor Diffusion in GaN: A DFT study

1. Growth

Karol Kawka[1]
Pawel Kempisty[1], Michal Bockowski[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142, Warsaw, Poland

Abstract text: Gallium nitride (GaN) is a key material for high-performance electronic and optoelectronic devices, where precise doping control is essential. Silicon (Si), germanium (Ge), and tin (Sn) serve as key donor dopants for n-type GaN, but their incorporation behavior remains a critical factor in device fabrication. This study investigates the diffusion mechanisms of these donors in bulk GaN using first-principles density functional theory (DFT) calculations, considering both neutral and n-type charge states.

DFT calculations were conducted using the SIESTA software within the Generalized Gradient Approximation (GGA). Vacancy-mediated diffusion mechanisms were analyzed through Nudged Elastic Band (NEB) calculations. Additional phonon calculations were conducted, and based on these, changes in vibrational free energy and their impact on the effective energy barrier were determined. Migration barriers were determined for multiple crystallographic directions to understand diffusion anisotropy.

For Si and Ge, significant variations in energy barrier heights are observed depending on the crystallographic direction. In the case of Si, the computed values are 3.2 eV along the [11-20] direction, 3.8 eV along [0001], and around 10 eV along [1-100], indicating a strong dependence on crystallographic orientation. For Ge, diffusion calculations were performed along the [11-20] and [0001] directions for both neutral and n-type charge states. The computed energy barriers in the [11-20] direction were 2.6 eV for neutral Ge and 2.3 eV for n-type Ge, whereas in the [0001] direction, the barriers were 3.5 eV and 3.1 eV, respectively. These results indicate that Ge exhibits a little lower migration barriers compared to Si, particularly in the lateral direction, suggesting potentially enhanced diffusion.

Preliminary results for Sn indicate diffusion barriers of approximately 2.3 eV along the [0001] direction, suggesting a distinct diffusion behavior compared to Si and Ge, i.e., higher mobility. This makes Sn particularly interesting for further investigation.

This study provides insight into the diffusion behavior of Si, Ge, and Sn in bulk GaN, with significant anisotropy and charge-state-dependent effects. A comparison with available experimental studies on dopant diffusion after ion implantation and UHPA annealing will be conducted to validate these theoretical predictions.

GR-Thu-P5* - Limited Diffusion of Silicon in GaN: A DFT Study Supported by Experimental Evidence

1. Growth

Karol Kawka[1]
Pawel Kempisty[1], Akira Kusaba[2], Kacper Sierakowski[3], Michal Bockowski[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142, Warsaw, Poland
[2] Research Institute for Applied Mechanics, Kyushu University, Fukuoka 816-8580, Japan
[3] Department of Materials Science and Engineering at North Carolina State University, Raleigh, NC 27606, United States of America

Abstract text: Silicon (Si) is the primary donor dopant for gallium nitride (GaN), incorporated via epitaxial growth methods or ion implantation. Precise control over Si diffusion remains a critical challenge, especially for high-performance device applications. In this study, we investigate the diffusion mechanisms of Si in bulk GaN using first-principles density functional theory (DFT) calculations supported by ultra-high-pressure annealing (UHPA) experiments.

The DFT calculations were performed using the SIESTA code, focusing on vacancy-mediated diffusion mechanisms. Minimum energy paths (MEPs) and activation barriers along different crystallographic directions were determined using the nudged elastic band (NEB) method. The results show that the diffusion barriers vary depending on the crystallographic direction but remain high in all cases. The lowest diffusion barrier is 3.2 eV along the [11-20] direction, increasing to 3.8 eV along the [0001] direction. The highest diffusion barrier is observed along the [1-100] direction, reaching approximately 9.9 eV, making diffusion in this direction extremely unlikely. Direct exchange and ring-like migration mechanisms exhibit prohibitively high energy barriers exceeding 12 eV, rendering them unlikely in practical conditions. Additionally, phonon calculations indicate that temperature-induced reductions in effective diffusion barriers are minimal, confirming the limited diffusion of Si even at elevated processing temperatures.

Experimental validation was conducted on Si-implanted GaN samples subjected to ultra-high-pressure annealing (UHPA). This process was performed at temperatures up to 1450°C under a nitrogen pressure of 1 GPa. Secondary ion mass spectrometry (SIMS) measurements confirmed that no changes occurred in the Si concentration profiles for annealing processes carried out under different physical conditions. These findings suggest that Si diffusion in GaN is negligible under typical device processing conditions, ensuring the stability of doped regions and supporting precise electronic applications.

This study resolves inconsistencies in previous reports and enhances understanding of Si behavior in GaN. The findings provide crucial insights for optimizing doping strategies in GaN-based electronics and optoelectronics, ensuring stable and precise doping profiles for high-performance applications.

GR-Thu-P6 - Theoretical Analysis and Fabrication of Epitaxial Cubic Boron Nitride-Diamond Heterojunctions with Multiple Crystal Orientations

1. Growth

Mark Polking[1]
Shikha Saini[2], Jeffrey Daulton[1], Bilge Yildiz[2]
[1] MIT Lincoln Laboratory
[2] Massachusetts Institute of Technology

Abstract text: Cubic boron nitride (c-BN) is an ultra-wide bandgap semiconductor that has a thermal conductivity and critical breakdown field ~5x and 4x higher than GaN, respectively, and among the highest known figures of merit for power switching and RF devices. In addition, the low 1.3% lattice mismatch with respect to diamond enables the formation of epitaxial heterojunctions suitable for modulation-doped field effect transistors (MODFETs) analogous to current GaN-based devices. Despite the immense potential of c-BN, preparation of high-quality c-BN has largely been limited to sub-mm-scale crystals grown by high-pressure, high-temperature techniques, limiting its practical utility. In addition, little is currently known about the electronic structure, doping, and defects of diamond/c-BN heterojunctions, which limits the rational design of future devices. In this talk, we will present results of a rigorous and comprehensive combined theoretical and experimental analysis of diamond/c-BN heterojunctions with multiple crystallographic orientations. We will first present a detailed investigation of the electronic structures, interfacial defects, bulk defects, and defect complexes, and chemical doping potential of heterojunctions with (100), (110), and (111) orientations performed using density functional theory (DFT) calculations with highly accurate hybrid functionals. This work represents, to our knowledge, the most comprehensive and accurate theoretical analysis of diamond/c-BN heterojunctions. We will then present the results of a process for preparation of diamond surfaces with all three of the above orientations and sub-Angstrom surface roughness levels using a combination of chemical treatments, a unique atomic layer etching process, and mechanical polishing. The exceptional quality of these surfaces provides an ideal starting point for growth of high-quality epilayers. In the final portion of the talk, we will present results of recent growth trials performed using these specially prepared substrates in a unique, multi-mode deposition system that demonstrate high-quality, phase-pure epilayers of c-BN on substrates of all three orientations.

GR-Thu-P7* - A cascade model for the defect-mediated electrochemical etching of porous gallium nitride distributed Bragg reflectors

1. Growth

Ben Thornley[1]
Maruf Sarkar[1], Saptarsi Ghosh[2], Menno J. Kappers[1], Rachel A. Oliver[1]
[1] Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom
[2] Department of Electronic and Electrical Engineering, Swansea University, Swansea, United Kingdom

Abstract text: Introduction of nanoscale porosity into gallium nitride (GaN) epitaxial structures provides a new dimension for materials engineering and device optimisation. Distributed Bragg reflectors (DBRs) based on this framework, utilising alternating porous/non-porous layers to achieve constructive interference of light, have demonstrated competitive reflectance and are suitable for mass production.

GaN is porosified by electrochemical etching (ECE) in an aqueous solution with an applied bias against a counter electrode. ECE is conductivity selective, leaving insulating material unaffected and porosifying n-type GaN. DBRs are hence prepared by etching of alternating layers of highly Si-doped and undoped GaN in epilayer stacks, where threading dislocations (TDs) are etched into nanopipes in undoped layers and laterally into full pores in doped layers.

In this work, we perform volumetric FIB-SEM tomography on three 5-period porous GaN DBRs etched at 5, 8 and 10 V respectively, and we demonstrate the complex interplay of different TDs as etching pathways, compiling a new ‘cascade model’ of etching. Tomographic datasets, captured with a Zeiss Crossbeam 540 instrument assisted by the Atlas Nanotomography software package, are compiled into large, high-resolution 3D reconstructions to explore pore morphology and dislocation etching. Prior work describes etching as following a ‘kebab’ model, where TDs etch into individual structures consisting of a central nanopipe and emanating pores in successive doped layers. Using tomography, we instead reveal that TDs do not each form isolated ‘kebabs’, but that pore structures form as interconnected and complex networks involving many distinct porous fields and TDs. However, increasing etching voltage causes a tendency towards traditional ‘kebab’ behaviour.

We then use the information-dense tomographs to generate statistics about the etching behaviour of different dislocations in the various layers at different etching voltages. This is done by the colour-coding of reconstructed frames of etching onset for the five porous layers, tracking the positions of the centres of etched dislocations. These show that high-voltage ECE samples see a progressive increase in etched TDs through the stack, but low-voltage ECE samples see the opposite.

GR-Thu-P8* - Analysis of GaN substrate polishing damage and its propagation to GaN epi layers using multiphoton photoluminescence

1. Growth

Shota Fujiki[1]
Hideo Aida[2], Shugo Nitta[3], Natsuko Omiya[4], Hirofumi Hoshida[1]
[1] Lasertec corporation, Yokohama 222-8552, Japan
[2] Nagaoka University of Technology, Nagaoka 940-2188, Japan
[3] Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya 464-8601, Japan
[4] Sanoh Industrial Co., Ltd., Koga 306-0041, Japan

Abstract text: Optimizing substrate processes for high-quality epi layers requires analyzing epi layer defects caused by substrate damage. The CL method has been used to analyze near-surface internal defects. However, the internal observation depth of this method is limited due to the low penetration depth of its wavelength.

In this presentation, we will discuss defect analysis using multiphoton photoluminescence (MPPL) to observe deep internal defects in GaN-on-GaN epi wafers. Our study aims to capture 3D images of linear internal defects propagating from the substrate, verified by the CL method, using a multiphoton excitation (MPE) microscope.

MPPL captures not only 2D profile images but also 3D profile images of linear internal defects. In these 3D images, the linear internal defects and filamentous planar defects originate from near the epi-substrate interface. The filamentous shape defects are considered to be dislocations in the substrate caused by stress, as shown in previous studies.

It is challenging to definitively determine the actual location of defects inside the sample from the mechanical depth displacement of the microscope. MPE microscopy observes photoluminescence (PL) light only at the focus point, similar to confocal microscopy. However, there are several differences between MPE microscopy and confocal microscopy, which simply captures reflected light. These factors make it difficult to determine the actual depth from which the observed PL light originates. We attempt to address this by inferring the depth based on qualitative information, such as changes in background brightness, presumed to be in the epi layer and substrate layer, and changes in morphology.

As for the challenge of quantitatively determining the actual depth position of MPPL images, it is feasible to reconstruct the 3D image by stacking the 2D images using the thickness information from the sample's design data.

We plan to validate our results by comparing the 3D profile images captured via this non-contact, non-destructive method with actual cross-sectional images captured by cross-sectional TEM. This will ensure the reliability and accuracy of our approach.

GR-Thu-P9 - Assessment of Subsurface Damage in GaN Substrates Induced by Mechanical Polishing

1. Growth
Natsuko Omiya[1]
Hideo Aida[2], Hidetoshi Takeda[2], Toshiro Doi[3]
[1] Sanoh Industrial Co. Ltd., Ibaraki, Japan/Nagaoka University of Technology, Niigata, Japan
[2] Nagaoka University of Technology, Niigata, Japan,
[3] Professor Emeritus of Kyushu University/Doi Laboratory Inc., Fukuoka, Japan

Abstract text: GaN substrates are commonly employed for the homoepitaxial growth of device thin films for high-efficiency GaN-based devices. From an industrial perspective, reducing the costs associated with the GaN wafering process is a significant issue in the mass production of the homoepitaxially grown GaN devices. The wafering process typically consists of rough grinding, mechanical polishing, and chemical mechanical polishing (CMP). Among these processes, developing the CMP process is challenging due to its low removal rate, which results in an increase of the wafering cost. To address this issue, two approaches can be considered: one is development of CMP process with high efficiency, another is minimizing subsurface damage (SSD) induced in subsequent processes, namely mechanical polishing. The removal thickness of the substrates in CMP process is determined to ensure the complete removal of all SSD induced by the mechanical polishing. To develop a mechanical polishing process that reduces SSD depth, an evaluation method for SSD that can be routinely applied to process development also needs to be considered.

Generally, cross-sectional transmission electron microscopy (X-TEM) is used as a method for evaluating SSD depth. While it can accurately assess the depth of SSD, it is not suitable for daily work of development because it takes a lot of time for sample preparation. Therefore, an evaluation method for SSD that allows non-destructive and quick measurement while achieving accuracy close to X-TEM is necessary. So far, various methods, such as X-ray diffraction (XRD), Raman imaging, and cathodoluminescence (CL) imaging, have been used for evaluation of SSD depth of GaN substrates, however, the accuracy of these evaluation results and their usefulness from the perspective in development of wafering process have not been discussed. In realizing low-cost wafering process for GaN substrates, it is important to discuss evaluation methods of SSD that are simple and accurate.

In this paper, we comprehensively assessed the depth of SSD induced by mechanical polishing using various evaluation methods. Based on the results obtained from reliable X-TEM, we evaluated the validity of the results assessed by XRD, Raman imaging, and CL imaging method. As a result, the superiority of these methods as measurement techniques to accelerate technology development was confirmed.

GR-Thu-P10* - Development of monitoring technique for damaged layers using electrical resistance during power device polishing

1. Growth

Ryota Koshino[1]
Hozumi Yasuda[1], Koichi Masuya[1], Keiji Honjo[1], Hideo Aida[2]
[1] EBARA corporation , Kanagawa 251-8502 , Japan
[2] Nagaoka University of Technology , Niigata 940-2188 , Japan

Abstract text: Gallium nitride (GaN) and other materials are attracting attention as next-generation power semiconductor device materials. Compared to silicon, a conventional semiconductor material, GaN has a band gap about three times larger and a critical electric field strength about 11 times larger, and is compatible with operation under high heat and has high voltage resistance. For this reason, it is expected to reduce loss, increase output, and miniaturize equipment.

However, these crystalline materials are classified as difficult-to-process materials, and are highly hard and chemically stable. In substrate processing, a damaged layer called the processing-affected layer that occurs on the surface during the slicing process must be completely removed in a subsequent process, so multiple planarization processes are used, with chemical mechanical polishing as the final process. In order to optimize this process, it is important to have a technology to evaluate the amount of processing-affected layer, but the conventional measurement methods have issues such as stopping the processing process once and taking time to measure.

In this study, we focused on the resistance change of the substrate as a method to monitor the amount of processing-affected layer in a short time in order to grasp the change in the processing-affected layer during power device substrate polishing, and measured the substrate resistance using an eddy current resistance measuring device. Based on these results, we attempted to evaluate the process-induced damage layers in GaN substrates.

The substrate resistance was measured for each substrate thickness under two different mechanical polishing conditions, and it was confirmed that the relationship between substrate resistance and substrate thickness changes depending on the amount of process-affected layer. In addition, based on the obtained results, a method for monitoring the process-affected layer was examined, and the possibility of using sheet resistance to detect the point at which the process-affected layer is minimized was suggested. This evaluation method is expected to contribute to the acceleration of process evaluation aimed at reducing process-affected layer.

GR-Thu-P11* - Direct fabrication of record low resistivity (< 10-4Ω·cm2) contacts for n-type AlxGa1-xN (x>0.8)

1. Growth

Tingang Liu[1]
Haicheng Cao[1], Mingtao Nong[1], Zhiyuan Liu[1], Zixian Jiang[1], Kexin Ren[1], Xiaohang Li[1]
[1] Advanced Semiconductor Laboratory, Electrical and Computer Engineering Program, CEMSE Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Kingdom of Saudi Arabia

Abstract text: Al-rich AlGaN has emerged as a promising material for high-power, high frequency, and optoelectronic applications. However, achieving low contact resistivity in Al-rich n-type AlGaN films remains a critical challenge that directly impacts device performance. While strategies such as graded layers have shown promise, they require intricate epitaxy control and extra etching process. This study presents a solution by employing an optimized metallization technique directly on Al-rich n-type AlGaN films. This approach not only simplifies the fabrication process but also avoids complications associated with extra growth and etching steps.

Figure (a) and (b) show the epitaxy structures of $Al_{0.86}Ga_{0.14}N$ (A-8) and $Al_{0.9}Ga_{0.1}N$ (A-9). The doping concentration was controlled as 5×10^{18} cm^{-3} for each sample. X-ray diffraction (XRD) 2θ-ω scans of A-8 and A-9 were shown in Figure (c) with calibrated sapphire peaks. The surfaces of these samples exhibit smooth textures with root mean square (RMS) roughness values of 374 nm and 426 nm, as demonstrated in Figures (d-e). Circular transmission line measurement (CTLM) was employed to determine the contact resistivity of A-8 and A-9. Figure (f) illustrates the CTLM structure, featuring an inner radius of 600 μm and electrode distances ranging from 5 to 50 μm. After sample growth and cleaning, a Ti/Al/Ti (20/80/120 nm) was deposited onto the samples via sputtering. Both A-8 and A-9 underwent rapid thermal annealing (RTA) at 950°C for 90 seconds under N_2 atmosphere using the JetFirst 200C system.

I-V characteristics were shown in Figures (g-h). A-8 exhibited higher current due to its lower activation energy and higher carrier concentration compared to A-9. To evaluate contact resistivity (ρ_c), data processing and linear fitting of R_t vs. ln (R_n/R_0) were performed, as detailed in Figures (i-j). A-8 has a ρ_c of $2.01\times10^{-5}\Omega\cdot cm^2$, and A-9 has a ρ_c of $1.80\times10^{-4}\Omega\cdot cm^2$. Figure (k) benchmarks our results against direct metallization on n-type Al-rich AlGaN and AlN, showcasing our record-low contact resistivity. The high performance of our metallization strategy is attributed to the formation of an Al-Ti-N layer at the interface, which enhances nitrogen vacancy creation and increases carrier concentration near the surface. This approach avoids the formation of Al-Au alloy in conventional Ti/Al/Ti/Au stacks, thus preventing Ti out diffusion.

GR-Thu-P12 - Electrochemical Process Design for Integrated Components based on Porous Gallium Nitride

1. Growth

Florian Meierhofer[1]
Matthias Hoormann[1], Frederik Lüßmann[1], Christoph Margenfeld[1], Karla Paz[2], Jyoti Bej[1], Anastasiia Sorokina[1], Stefanie Kroker[1], Carsten Ronning[2], Andreas Waag[1]
[1] Nitride Technology Center, Institute of Semiconductor Technology, Technische Universität Braunschweig, 38106 Braunschweig, Germany
[2] Institute of Solid State Physics, Friedrich-Schiller-Universität Jena, 07743 Jena, Germany

Abstract text: In recent years, the dopant-selective electrochemical etching (ECE) method [1-2] received significant attention due to its ability to transform solid epitaxial nitrides into porous layers with novel material properties that cannot be attained solely with established (Al/Ga/In)-nitrides. For example, in comparison to conventional wurtzite GaN, layers of porous GaN exhibit a reduced refractive index (e.g. $n_{porGaN} \sim 1.8$ vs. $n_{GaN} \sim 2.5$), an augmented surface-to-volume ratio (e.g. $S/V > 10^7$ m^2/m^3 for 25 nm pore diameter and 50 % porosity), an enhanced piezoelectric coefficient ($d_{33,porGaN} \approx 8$ pm/V vs. $d_{33,GaN} \approx 3$ pm/V, [3]), and a lower elastic modulus ($E_{porGaN} \approx 193$ GPa vs. $E_{GaN} \approx 361$ GPa, [4]). Concurrently, porous GaN remains thermally and electrically conductive (TC $\approx$ 1–24 W/mK, $\sigma \approx$ 1–20 S/cm, [5]), rendering it an intriguing candidate for various applications in the field of photonics, optoelectronics, sensors, among other nitride-based devices.

In our contribution, we undertake a comprehensive description of the underlying mechanisms during the ECE process, and accentuate the seminal advancements that have been achieved for this technology in the context of porous nitrides. According to the extant literature from the past two decades, ECE-made porous nitrides can be categorized into three types: top-porous (TP), subsurface-porous (SP), and laterally patterned porous (LPP). The fabrication routes, material properties, and applications demonstrated in the literature for these categories will be briefly discussed herein. The second part of the contribution will focus on our present activities regarding integrated photonic components based on porous nitrides. In this context, we will present more insights in the ECE process, sample analysis, and our latest findings in tuning the etch-selective properties of ion-implanted nitrides of the LPP approach in combination with porGaN/GaN waveguide properties.

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GR-Thu-P13* - High-Temperature Annealing of Ion-Implanted Aluminum Nitride: Effect of Point Defects on Crystal Recovery

1. Growth

Christoph Margenfeld[1]
Lukas Peters[1], Karl Kreuzer[1], Carsten Ronning[2], Jan Krügener[3], Jana Hartmann[1], Andreas Waag[1]
[1] Nitride Technology Center, Institute of Semiconductor Technology, Technische Universität Braunschweig, Braunschweig, Germany
[2] Institute of Solid State Physics, Friedrich-Schiller-Universität Jena, Jena, Germany
[3] Institute of Electronic Materials and Devices, Leibniz Universität Hannover, Hannover, Germany

Abstract text: Over the last decade, high-temperature annealing (HTA) of aluminum nitride (AlN) on sapphire templates has developed into a mature technology for the manufacturing of ultraviolet light emitting diodes and ultra-wide-bandgap electronic devices, offering high crystalline quality and ease of scalability at reduced process complexity. Despite the widespread adoption, an in-depth understanding of the mechanisms at play during the recrystallization remains elusive.

A prevailing consensus suggests that dislocation motion during HTA mainly occurs via dislocation climb, which is predominantly driven by the consumption of metal vacancies. However, our data suggests that additional factors can influence the dislocation climb mobility. We designed a set of experiments where AlN-on-sapphire templates grown either by sputter epitaxy or metalorganic vapor phase epitaxy (MOVPE) are extrinsically doped by ion implantation with a multitude of native and foreign species. By comparing the crystalline quality of the same AlN layers annealed with and without prior ion treatment, we intend to shed light onto the impact of the prevailing point defect landscape on the dislocation motion during annealing. Indeed, we find that some species can further enhance the crystalline quality of the annealed templates with respect to the unimplanted samples, while other species can hamper the process significantly. At first glance, no systematic behavior across group III, group V, donor- or acceptor-type species can be discerned.

In this contribution, we aim to obtain a deeper understanding of the point defect landscape in the ion-implanted and subsequently annealed AlN templates and try to correlate it to the observed influence on crystalline quality. Cathodoluminescence spectroscopy and optical transmission measurements evaluated by the Swanepoel method [1] are employed to characterize the presence of common point defects via their characteristic emission or absorption bands. By applying the learnings from this study, we can manufacture templates with a dislocation density below $4 \cdot 10^8$ cm^{-2} for both sputter- and MOVPE-deposited layers.

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GR-Thu-P14* - Mitigation of Silicon Interface Contamination for Improved Selective Area and Patterned Regrowth

1. Growth

Francesco Marcantoni[1]
Amirhossein Esteghamat[1], Uiho Choi[1], Elison Matioli[1]
[1] Power and Wide-band-gap Electronics Research Laboratory, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Abstract text: Selective area and patterned regrowth are crucial for fabricating laterally patterned heterostructures in semiconductor technologies. In GaN devices, they are commonly used for regrown n-type ohmic contacts. However, dry-etch-induced defects and Si contamination, both acting as donors, hinder the performance of regrown u-/p-type GaN patterns [1-3]. Notably, Si accumulates significantly even from air exposure before regrowth [2]. Strategies such as low-power etching and post-etch treatments [2,3] mitigate these effects: while etch damage can be recovered, Si contamination remains high enough to degrade device performance. A common approach combines UV-Ozone oxidation and acid treatment (HF, HCl) to remove Si contaminants, reducing levels down to ~1×10^{18} cm^{-3} [2,3]. While effective for planar etched-and-regrown interfaces [3], this concentration is still high enough to cause leakage along non-planar regrowth interfaces, limiting device performance [1,3]. Further reduction of Si contamination is essential to enhance regrown device performance across different GaN planes.

Here, we demonstrate that post-etch hot TMAH treatment, widely used for etch-damage removal [4-6], significantly reduces Si levels on both c- and m-plane GaN—by up to two orders of magnitude. Compared to UVO-HF, UVO-HCl, and hot KOH, it achieves greater effectiveness. SIMS and SEM-AFM suggest that Si is removed through removal of the contaminated and damaged layer rather than oxidation and SiO_2 removal. Based on these promising results, the impact of low-power etching [2, 3] and hot TMAH treatment on the behavior of etched-and-regrown GaN devices will also be presented, providing further insights into the potential of this approach. This would not only enable more performant vertical power devices, but it would also open the possibility for novel GaN-based regrown devices.

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GR-Thu-P15 - Oxygen Plasma Etching for Tailored Thru-Hole Densities in Graphene Masks for thru-hole epitaxy

1. Growth
Su Young An[1]
Chinkyo Kim[1]
[1] Kyung Hee University, Seoul, Korea

Abstract text: In thin-film heteroepitaxy, the mismatch in lattice constants between the film and the substrate is a key factor affecting defect density. Thru-hole epitaxy (THE) is an effective approach that leverages thru-holes in a mask material to mitigate defects in films experiencing significant lattice mismatch. In THE, the distribution of thru-holes—including their size and density—plays a crucial role in determining the defect levels in the grown film. Therefore, optimizing the thru-hole density in the mask material is essential for enhancing film quality. This study investigates the precise control of thru-hole density in graphene, a mask material that can be easily etched using oxygen plasma. By adjusting the oxygen plasma etching time, the thru-hole density can be finely tuned, enabling the fabrication of masks with tailored thru-hole configurations.

GR-Thu-P16* - Photoluminescence analysis of time-dependent isotropic dry etching for reducing sidewall nonradiative recombination of n-GaN in micro-LEDs

1. Growth

Zhengfei Wei[1]
Sung-Jin Cho[1], Andrew Newton[1]
[1] Oxford Instruments Plasma Technology, Severn Beach, Bristol BS35 4GG, United Kingdom

Abstract text: Micro-light-emitting diode (μLED) technology is emerging as a key solution for next-generation high-resolution displays, especially for augmented-reality (AR) and Virtual Reality (VR) applications. However, achieving highly efficient, ultra-small μLEDs remains a significant technical challenge due to strong non-radiative recombination at the sidewalls. This recombination, primarily attributed to Shockley-Read-Hall (SRH) defects arises from sidewall and surface damage induced during Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) process [1-3].

In this work, we demonstrate a significant improvement in photoluminescence (PL) intensity on n-type Gallium Nitride (n-GaN) surfaces by optimising the etch time of a damage-recovery isotopic dry etch following a mesa dry etching process. This treatment effectively removed the plasma-damaged layer formed on the surface of the nGaN during the mesa etching process. The damage is measured at the base of the etch rather than the masked mesa top. As a result, the average PL intensity exhibits an approximate 173% increase after 60 minutes-etching, compared with the n-GaN without isotropic etching. This enhancement is attributed to the reduction of SRH non-radiative recombination sites associated with sidewall and surface damage. Additionally, Kelvin probe force microscopy (KPFM) imaging revealed a progressive increase in surface potential with deeper isotropic etching, directly correlating with the observed improvement in PL intensity. To further understand this mechanism, we will use cathodeluminescence (CL) to investigate the role of strain relaxation and its interaction with sidewall surface non-radiative recombination, revealing their direct impact on the improvement of PL intensity. Furthermore, μLEDs currently being fabricated are expected to demonstrate a significant increase in external quantum efficiency (EQE). These advancements address critical obstacles in μLED fabrication and pave the way for a significant step towards commercialisation of μLED displays for AR/VR, phones and smart watches.

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GR-Thu-P17* - Porous GaN: Anion-Specific Etching Mechanisms and Morphological Control

1. Growth

Thom Harris-Lee[1]
Benjamin Thornley[1], Menno Kappers[1], Rachel Oliver[1]
[1] Cambridge Centre for Gallium Nitride, University of Cambridge, Cambridge, UK

Abstract text: Porous GaN has emerged as a promising material for enhancing the performance of LEDs, sensors, and high-power electronics.[1] Electrochemical etching (ECE) of n-type GaN creates high surface area structures with tunable porosity, improving light extraction, aiding strain relaxation and defect reduction, and enabling composite formation through pore infiltration. However, understanding of the electrochemical mechanisms driving the etching process remains very limited.

ECE is often conducted by immersing n-type GaN into an oxalic acid solution and applying an anodic bias relative to a counter electrode. In this setup, the lack of precise control over etching conditions limits mechanistic understanding, resulting in purely empirical optimisation. To mitigate this, sodium oxalate is added to the oxalic acid solution to create an oxalate buffer, offering enhanced pH control while maintaining the low pH of oxalic acid. By comparing different ratios of oxalic acid and sodium oxalate, the key variable controlling the etching mechanism and resulting morphology is identified.

Oxalic acid, as a weak acid, establishes an equilibrium between its mono- and dianionic species, whereas sodium oxalate fully dissociates into oxalate dianions. Through systematic ECE studies, it is demonstrated that the observed differences in porous structures correspond directly to the dominant anionic species in solution, rather than pH alone. Further, the relative proportion of dianions in an oxalic acid solution can be increased by decreasing the solution concentration, which correlates with a transition in porous morphology. These findings are extended to a range of etchant solutions, showing that the predominant influence on etching dynamics and pore morphology is the anion composition, further refining the understanding of morphological variability across ECE systems.

Deepening our understanding of the ECE process is essential for optimising pore morphology, improving reproducibility, and ensuring scalable fabrication whilst reducing reliance on hazardous reagents. These findings offer new insights into the interplay between etching conditions and reaction mechanisms, enabling the bespoke design of advanced porous GaN architectures tailored for specific next-generation optoelectronic and electronic applications.

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GR-Thu-P18* - Preparation of Highly Smooth Surfaces on OVPE-GaN Substrates via Photoelectrochemical Reaction-Assisted Polishing

1. Growth

Kiyoto Kayao[1]
Tatsuya Fukagawa[1], Daisetsu Toh[1], Jumpei Yamada[1], Shigeyoshi Usami[1], Masayuki Imanishi[1], Yusuke Mori[1], Yasuhisa Sano[1]
[1] The University of Osaka, Suita, Osaka, Japan

Abstract text: The oxide vapor phase epitaxy (OVPE) method has gained attention for growing GaN crystals with high impurity concentrations and low dislocation density[1]. OVPE-GaN substrates facilitate the fabrication of vertical GaN power devices with low on-resistance. However, achieving a highly smooth substrate surface is essential for their theoretical performance. Conventionally, chemical-mechanical polishing (CMP) reduces substrate surface roughness by oxidizing the GaN surface and removing the oxidized layer with abrasives. However, CMP-polished OVPE-GaN surfaces become rough due to variations in impurity concentration distribution. This impurity distribution originates from the differences in growth facets during OVPE. In CMP, high-impurity concentration regions, which are chemically unstable, are removed more rapidly than low-impurity concentration regions, leading to the formation of protrusions. These surface irregularities can lead to bunching steps during epitaxial growth, ultimately degrading device performance. Therefore, eliminating this unevenness is critical.

We propose a finishing process that uses photoelectrochemical (PEC) oxidation on OVPE-GaN substrates after CMP to address this issue. In this process, the GaN surface is oxidized via PEC oxidation induced by UV irradiation in an electrolyte, and the resulting oxides are then removed through chemical etching or polishing. Notably, the PEC oxidation rate is higher in low-impurity concentration regions than in high-impurity concentration regions. Consequently, the protrusions formed during CMP, corresponding to low-impurity-concentration regions, are preferentially removed. To enhance oxide removal, we applied catalyst-referred etching (CARE), a polishing method that selectively etches from the highest points on the surface via a catalytic reaction[2]. Combining CARE with PEC oxidation is expected to improve the efficacy of protrusion removal. After applying this finishing process to CMP-processed OVPE-GaN substrates, the surface unevenness was removed, and the surface roughness (Sq) improved from 1.07 nm to 0.61 nm. These findings significantly contribute to developing high-quality GaN substrates for vertical power device applications.

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GR-Thu-P19* - Qualification of AlN substrates after different surface treatments

1. Growth

Julia Schwar[1]
Gloria Kurth[1], Gleb Lukin[1], Roland Weingärtner[1], Sven Besendörfer[1]
[1] Fraunhofer Institute for Integrated Systems and Device Technology IISB, 91058 Erlangen, Germany

Abstract text: Aluminium nitride (AlN) is an emerging ultra-wide bandgap with a direct bandgap of 6.0 eV and a critical field of 15.4 MV/cm, and thus suitable for power and RF applications. However, one of the remaining challenges is the time consuming and costly process technology ranging from crystal growth to Epi-Ready wafers as well as the realization of Epi-Ready surfaces themselves [1]. To verify surface as Epi-Ready, epitaxy can be performed. However, a non-destructive method to evaluate the spatial distribution of process-induced crystalline defects would be highly beneficial to save time and costs. This enables more efficient surface preparation and substrate classification for epitaxy and device processing.

This study investigates the correlation between subsurface damage and wafer bow induced by residual stress in AlN substrates. The primary focus is on characterizing surface roughness, waviness, and subsurface damage. Quantitative surface topography and roughness measurements are performed using tactile and optical profilometry after different surface treatments. To map surface damage, dislocations, and defect clusters on a full wafer scale, X-ray topography (XRT) is employed in both reflection and transmission modes. This method provides qualitative imaging of local inhomogeneities in the surface and subsurface regions, which is essential for qualifying the epi-ready surface after polishing. By precisely locating the remaining polishing scratches, a quantitative comparison with optical profilometry was performed to identify the regional topology. Additionally, XRT in transmission mode was experimentally utilized to capture cross-sectional recordings for a comparative analysis of front- and backside damage. The implementation of non-destructive evaluation techniques will enhance process efficiency, reduce costs, and improve the selection of high-quality AlN substrates for more reliable and scalable power electronics and optoelectronic devices.

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GR-Thu-P20* - Study on slicing process of GaN bulk wafer using fixed abrasive wire saw

1. Growth

Shinya Moriyama[1]
Akira Oga[1], Hideo Aida[2], Hidetoshi Takeda[2], Tatsuki Otsubo[1], Takanori Yazawa[1]
[1] Graduate school of engineering, Nagasaki University, Nagasaki, Japan
[2] Nagaoka University of Technology, Niigata,Japan

Abstract text: Currently, GaN power devices are mostly horizontal structured devices fabricated by heteroepitaxial growth, but if vertical GaN devices are commercialized, they can support higher breakdown voltage and higher current operation, and are expected to bring innovation to the power electronics field, including EVs. For this purpose, homo-epitaxial growth (GaN on GaN) using GaN bulk substrates is necessary, and the establishment of mass production technology for GaN bulk wafers is an issue.

In this study, the slicing process using a multi-wire saw, which is part of the wafer fabrication process, was studied. The multi-wire saw is a cutting method that can produce more than a hundred wafers in a single process by pressing a “fixed abrasive wire tool,” which is a piano wire electrodeposited with diamond abrasive grains, onto an ingot while running at high speed. However, cracks and stresses remain on the surface, as well as warpage and thickness variation. Since these must be removed in the subsequent polishing process, it can be said that the efficiency of the entire wafer fabrication process depends on the quality of the slicing process. However, little is currently known about GaN bulk wafer slicing, and basic research to prepare for future technological trends is essential.

A simplified scratch test was used to investigate the slicing mechanism of GaN bulk wafers. The force applied at the moment of scratching was measured by a built-in force sensor. Scratch marks were measured by optical microscopy, SEM, Cathodoluminescence, and Raman spectroscopy to evaluate the damage to the GaN wafer surface. Furthermore, the state of the abrasive grains after scratching was observed by SEM. As a result, it was confirmed that the nickel plating layer peels off and the edge of the diamond abrasive protrudes when the abrasive grains strike the work material, and at that instant, a linear scratch mark is formed due to the high stress state. Furthermore, it was confirmed that dislocations propagated along the crystal direction starting from the scratch marks. It was also confirmed that the nickel plating layer holding the abrasive grains slides on the substrate, causing damage to the crystal. Furthermore, lateral cracks were observed inside the material, starting from scratch marks, suggesting a brittle mode of material removal.

GR-Thu-P21* - Wafer-scale single-crystalline GaN-based heterogeneous integration material by ion-cutting technique

1. Growth
Tiangui You[1]
Jiaxin Ding[1], Jialiang Sun[1], Xin Ou[1]
[1] Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai, China

Abstract text: Heterogeneous integration of gallium nitride (GaN) film on the complementary metal-oxide-semiconductor (CMOS)-compatible Si(100) substrate provides a material platform for the future high performance chips with multi-function. Recently, we have developed the ion-cutting technique for the fabrication of GaN thin film, with which a 2-inch wafer-scale single-crystalline GaN film is transferred from the commercialized bulk GaN wafer onto Si(100) substrate. The H^+ implantation fluence for exfoliation of GaN film is as low as 2.5×10^{17} cm^{-2} and the full width at half maximum (FWHM) of the (0002) x-ray rocking curve (XRC) of GaN film is 64.8 arcsec. The threading dislocations density (TDD) is calculated to be 4.8×10^5 cm^{-2} based on the CL measurement, which is similar to that of the sliced bulk GaN (2.8×10^5 cm^{-2}). The sliced bulk GaN wafer is recycled, which is beneficial to reduce the cost and to enhance the mass application of ion-cutting technique to GaN. The exfoliation mechanism of H-implanted GaN is investigated. The activation energy for slicing GaN is only 2.08 eV owing to the high-quality of the GaN wafer, while the wide residual damage band is still an obstacle to improve the quality of the GaN film.
Furthermore, the defect evolution in GaN thin films transferred onto Si(100) substrate via ion-cutting technique was thoroughly studied. The results of The Rutherford backscattering in channeling mode (RBS/C) suggest that the nano cavity defects and residual hydrogen (H) ions in the as-transferred GaN thin film evolve into larger size cavity defects after high-temperature post-annealing due to the Ostwald ripening mechanism and migration-coalescence mechanism, whereas the GaN lattice is recovered. The effect of defects caused by H ions on the optical properties of GaN film is investigated by temperature-dependent photoluminescence. The near-band-emission was quenched in the as-transferred GaN film while reappeared after post-annealing.
The successful demonstration of wafer-scale single-crystalline GaN film on Si(100) substrate will be of great benefit to the integration of high performance GaN devices and Si CMOS integrated circuits (ICs) with mature process technology.

GR-Thu-P22* - Graphene-Coated Templates for Exfoliation of MOCVD-Grown GaN

1. Growth

Dominykas Augulis[1]
Arūnas Kadys[1], Ilja Ignatjev[2], Umut Kaya[3], Wolfgang Mertin[3], Gerd Bacher[3], Tadas Malinauskas[1]
[1] Institute of Photonics and Nanotechnology, Vilnius University, Vilnius LT-10257, Lithuania
[2] Center for Physical Sciences and Technology, Vilnius LT-10257, Lithuania
[3] University Duisburg-Essen, 47057 Duisburg, Germany

Abstract text: GaN-based materials are vital for optoelectronic and electronic applications, yet they face persistent challenges stemming from heteroepitaxy-induced strain, defect formation, and the high costs of homoepitaxial substrates. Additionally, emerging applications, such as freestanding flexible and bendable electronics, present opportunities for Group III nitrides to expand their technological reach further. Here, we explore a 2D material-assisted epitaxy approach leveraging graphene as a van der Waals interlayer to mitigate strain, reduce defect propagation, and enable the potential reuse of expensive substrates. In this epitaxy process, the growth mode can combine van der Waals epitaxy with either homoepitaxy or heteroepitaxy, as the interaction between the wafer and the epilayer occurs through a graphene layer that is transparent to the underlying substrate field, guiding the epitaxial orientation of the grown crystals [1].

Building on the work by J. Kim et al. [2], we present the MOCVD growth of GaN on graphene-coated substrates and examine both the structural quality and exfoliation feasibility. Experiments were conducted using graphene deposited through three different methods: wet transfer, laminator-assisted transfer, and direct CVD growth on GaN templates. Pre- and post-growth characterization using SEM, XRD, and Raman spectroscopy indicates that low to high-temperature growth on graphene yields GaN with high crystalline quality, as confirmed by XRD. However, harsh growth conditions likely damage the graphene interlayer, hindering subsequent lift-off. Conversely, low-temperature GaN growth preserves graphene integrity for simpler exfoliation but at the expense of reduced crystalline quality. Exfoliation trials using thermal release tape and an electrochemically deposited Ni stressor highlight the trade-off between growth temperature and lift-off efficiency. Overall, this study demonstrates that optimized process steps, particularly at the seed-layer deposition and high-temperature growth phases, must be achieved for high-quality GaN membranes that can be easily exfoliated. These findings pave the way for cost-effective substrate reuse strategies and open new avenues for flexible and bendable electronics.

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PC-Thu-P1* - Defects in AlGaN with varying Al content

2. Physics and characterization

Igor Prozheev[1]
Marcel Schilling[2], Tim Wernicke[2], Frank Mehnke[2], Michael Kneissl[2], Filip Tuomisto[1]
[1] Department of Physics and Helsinki Institute of Physics, University of Helsinki, HELSINKI, FINLAND
[2] Technische Universität Berlin, Institute of Solid State Physics, BERLIN, GERMANY

Abstract text: We study defects in $Al_xGa_{1-x}N$ layers grown by metal-organic chemical vapor deposition on AlN/sapphire with Doppler broadening method of positron annihilation spectroscopy technique. [1] The Al content was varied from 66 to 100% at high V/III ratio resulting from the active region growth conditions with a growth temperature of 1020 °C at a reactor pressure of 600 mbar in the presence of the total 16 slm of H_2 carrier gas.

In samples with 66 – 92% Al content, we observe positron trapping at cation vacancy defects present in the range of 1.0×10^{16} – 2.0×10^{18} cm^{-3}. The vacancy concentration increases with the increase in Al content. We expect the formation energy of V_{III} to be low thanks to the low C content ($[C] \leq 1.0\times10^{17}$ cm^{-3}) and high V/III ratio. [2] In the samples with 100% Al, we observe $[V_{Al}] \approx 3.0\times10^{17}$ cm^{-3}. The increase in the V_{III} concentration with the Al content correlates with a known decrease in internal quantum efficiency in AlGaN-based light emitting devices with Al content above 80%, suggesting that cation vacancies are important in trapping charge carriers and limiting the quantum efficiency. [3]

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PC-Thu-P2* - Characterisation of the Iron Defect Level in GaN and Dilute AlxGa1-xN Alloys

2. Physics and characterization

Christopher Dawe[1]
Piotr Kruszewski[2], Vladimir Markevich[1], Lijie Sun[1], Paweł Prystawko[2], Jerzy Plesiewicz[3], Matthew Halsall[1], Iain Crowe[1], David Binks[1], José Coutinho[4], Anthony Peaker[1]
[1] University of Manchester, Photon Science Institute, Manchester, United Kingdom
[2] Polish Academy of Sciences, Institute of High Pressure Physics, Warsaw, Poland
[3] Polish Academy of Sciences, Institute of High Pressure Physics and University of Warsaw, Faculty of Physics, Warsaw, Poland
[4] University of Aveiro, i3N, Aveiro, Portugal

Abstract text: $Al_xGa_{1-x}N$ epilayers are widely used in high electron mobility transistors (HEMTs) as well as ultraviolet LEDs and photodetectors. Optimizing device performance and reliabilty relies on the understanding of deep-level defects and sources of contamination during epitaxial growth. Notably, iron contamination can have a significant influence due to deep acceptor nature of Fe atoms at Ga sites (Fe_{Ga}), leading to electron compensation, increased on-state resistance and slower switching speeds of GaN-based power electronics [1].

In this study, a range of GaN and dilute $Al_xGa_{1-x}N$ ($x \leq 0.063$) epilayers were grown using metal-organic vapor phase epitaxy (MOVPE) on Ammono-GaN substrates. Fe contamination and its effects were investigated using secondary ion mass spectrometry (SIMS), photoluminescence (PL) and deep-level transient spectroscopy (DLTS) in conjunction with Laplace-DLTS [2]. Capacitance-voltage measurements of the Si-doped epilayers yielded free carrier concentrations of about 3×10^{16} cm^{-3}, with electrical and optical characterisation performed on vertical Ni/Au Schottky barrier diodes (SBDs) and virgin material, respectively.

The presence of iron in the AlGaN samples can be monitored by photoluminescence in the near infrared spectral region, with a prominent PL peak at ~1.3 eV, which has been attributed to the $^4T_1(G) \rightarrow {}^6A_1(S)$ spin-forbidden transition of the Fe^{3+} charge state [3]. In the DLTS analysis, an emission signal with its maximum shifting to higher temperature in the range from 315 K to 355 K with x increasing from 0 to 0.063 has been assigned to the “E3” trap. The activation energy for electron emission for this trap is found to vary from 0.6 eV in GaN to ~0.68 eV in $Al_{0.063}Ga_{0.937}N$. It is argued that this trap is related to the $Fe_{Ga}(-/0)$ energy level [4]. Correlating SIMS, PL and DLTS results reveal that the concentration of Fe in the $Al_xGa_{1-x}N$ epilayers increases towards the edge of the wafers. This could be attributed to contamination from the SiC-coated graphite susceptor that is used during MOVPE growth, aligning with previous reports [5].

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PC-Thu-P3 - Temperature dependence of charge carrier diffusion in GaN and AlGaN layers

2. Physics and characterization

Carsten Netzel[1]
Tim Kolbe[1], Johannes Enslin[1], Markus Weyers[1]
[1] Ferdinand-Braun-Institut, Berlin, Germany

Abstract text: AlGaN-based optoelectronic devices emitting ultra-violet light between 200 and 350 nm are currently undergoing continuous development. Extensive efforts are being made to improve the efficiency and lifetime of LEDs or the performance of laser diodes. Important aspects of optimization are p-side current transport, light extraction and absorption, as well as the device lifetimes. Repeated efforts are also made to increase the internal quantum efficiency of the light-emitting layers. Dislocation and point defect densities are reduced, strain management and heterostructure design are optimized. Interpreting results from optimization is often difficult because AlGaN heterostructures are complicated physical systems where characteristics like band gap inhomogeneity, strain and piezoelectric/spontaneous fields, high exciton binding energies, and relatively high densities of defects can interact.
A frequently studied topic for III-nitrides is the charge carrier diffusion length. It is an important parameter for the quantum efficiency because it co-defines the probability that charge carriers reach nonradiative recombination centers and are thus lost for light emission.
In the current study, we focus on the temperature dependence of charge carrier diffusion lengths in $Al_xGa_{1-x}N$ layers with $x \approx 0.47$ and compare them with GaN layers. In photoluminescence, buried quantum wells are excited by diffusion of charge carriers optically excited in an AlGaN or GaN top layer (diffusion in vertical direction). In cathodoluminescence, the radii of dark spots around dislocations are measured (lateral in-plane direction) [1]. Both experiments show the same results. The diffusion length is much smaller in the inhomogeneous AlGaN alloy, especially at low temperature. In GaN, around room temperature, the diffusion length decreases with increasing temperature because of phonon scattering [2]. In AlGaN, the diffusion length increases at higher temperature. Overcoming potential barriers with the help of higher thermal energies of charge carriers seems to outweigh the impact of thermally activated scattering processes in AlGaN.

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PC-Thu-P4* - PHONON MEAN FREE PATH - THERMAL CONDUCTIVITY RELATION OF AlxGa1−xN, AND β-Ga2O3 SEMICONDUCTORS

2. Physics and characterization

Pegah Ghanizadeh[1]
Namsoon Eom[1], Aylin Ahadi[1]
[1] Department of Industrial and Mechanical Sciences, Lund University

Abstract text: Ultrawide-bandgap (UWBG) semiconductors like $Al_xGa_{1-x}N$ and β-Ga_2O_3 emerge as a promising option for advancing next-generation high-power electronic devices [1], [2]. *AlGaN* preserves significant attention due to its unique capability of tuning the bandgap from 3.4 (eV) to 6 eV, enabling a nonlinear increase in the critical breakdown field. β-Ga_2O_3, with a wide bandgap of 4.8 eV, surpasses *GaN* and has cost-effective substrates, making it appealing for high-power electronics. However, field-effect transistors (FET) and Schottky-barrier diodes based on $Al_xGa_{1-x}N$ and β-Ga_2O_3 have shown superior performance to *GaN*, indicating their potential for overcoming this challenge. The pressing issue of local heat build-up and narrowing thermal pathways in such high-performance small scales devices is a significant challenge. To optimize the performance and ensure reliable operation, efficient dissipation of heat generated in the device is essential. This can be done by understanding the thermal transport of these systems at a short-length scale, in this case, lattice vibrations (i.e., phonons) [3]. One of the critical properties that characterize this behaviour is the phonon mean free path (MFP). This research offers a detailed analysis of phonon mean free path accumulation spectra in β-Ga_2O_3 and $Al_xGa_{1-x}N$ alloys with different Al fractions at different lattice temperatures by utilizing ab-initio and lattice dynamics calculations based on density functional theory (DFT) along with the Boltzmann transport equation (BTE). Our results indicated that the normalized cumulative thermal conductivity of alloys is notably reduced compared to that observed in pure systems. This effect is particularly pronounced for larger mean free paths (MFPs).

PC-Thu-P5 - In Situ Time-Resolved XPS Investigation of High-k Oxide Atomic Layer Deposition on (Al)GaN

2. Physics and characterization

Rainer Timm[1]
Shreemoyee Chakraborty[1], Nishant Patel[1], Byeongchan So[1], Minho Kim[2], Alexis Papamichail[2], Rosemary Jones[3], Erik Lind[4], Vanya Darakchieva[1]
[1] NanoLund and Department of Physics, Lund University, 221 00 Lund, Sweden
[2] Center for III-Nitride Technology, C3NiT-Janzén, Dept. Physics, Chemistry and Biology, Linköping University, 581 83 Linköping, Sweden
[3] Max IV Laboratory, Lund University, 221 00 Lund, Sweden
[4] NanoLund and Dept. Electrical and Information Technology, Lund University, 221 00 Lund, Sweden

Abstract text: Many GaN- and AlGaN-based power electronic devices are based on metal-oxide-semiconductor (MOS) stacks, where downscaling and leakage control require gate insulators with high dielectric constant, so-called high-k oxides. However, device performance and especially switching frequencies are often limited by the low quality of the (Al)GaN/high-k interface. Atomic layer deposition (ALD) is typically used for the formation of ultrathin, conformal high-k layers, where the choice of oxide material, ALD parameters, and pre-ALD cleaning methods strongly influence film and interface quality. Many important details about the physics and chemistry of the interface formation still remain unknown. Furthermore, until now all efforts to explore the high-k oxide film formation are based on *ex situ* approaches, meaning that film deposition and characterization of the resulting interface occur in separate steps.

Here, we will present a first time-resolved investigation of the ALD reactions of HfO_2 on (Al)GaN. We have used synchrotron-based ambient-pressure X-ray photoelectron spectroscopy (AP-XPS) and implemented the ALD process in the AP-XPS setup, mapping surface chemistry and electronic properties *in situ* during subsequent ALD half-cycles, which consisted of the deposition of tetrakisdimethylamido-hafnium (TDMA-Hf) and water. We observed a rather inefficient first ALD cycle, compared to other semiconductor ALD reactions, which improved with increasing aluminum content. Thickness and chemical composition of the resulting Hf-oxide film varied significantly if the order of the precursors was changed (TDMA-Hf first or water first). Both observations are against established ALD models and highlight the importance of in-depth studies for improving the quality of high-k layers on (Al)GaN.

In addition, we have used XPS to systematically investigate the chemical composition and electronic properties of the interface between different (Al)GaN substrates and HfO_2 or Al_2O_3 high-k oxide films, for different ALD temperatures, where Al_2O_3 layers typically resulted in a more stoichiometric oxide film. The choice of pre-ALD cleaning methods was also found to be of importance, which can enhance ALD efficiency but also result in significant interface contamination. We will discuss how our structural results can be easily implemented to improve device performance.

PC-Thu-P6* - Selective thermal etching fabrication of AlGaN/air distributed Bragg reflectors with > 200 nm stop-band

2. Physics and characterization

Pierre-Marie Coulon[1]
Benjamin Damilano[1], Maksym Gromovyi[1], Maud Nemoz[1], Sébastien Chenot[1], Blandine Alloing[1], Jésus Jésus Zúñiga-Pérez[1]
[1] Université Côte d'Azur, CNRS, CRHEA, Valbonne, France

Abstract text: III-Nitride Distributed Bragg Reflectors (DBRs) are essential components in optoelectronic and photonic devices, particularly in applications requiring high-reflectivity mirrors and optical confinement, such as vertical-cavity surface-emitting lasers, resonant cavity LEDs, and photodetectors. These DBRs are generally composed of alternating layers of GaN/AlN, GaN/AlGaN or GaN/AlInN. However, challenges such as strain accumulation, which introduce structural defects, and low refractive index contrast, which results in narrow stop-band widths of ≈30 nm, can hinder their performance.

In this work we fabricate AlGaN/air DBRs by leveraging of the higher thermal stability of AlGaN alloys with respect to GaN. First, 10 AlGaN/GaN DBR pairs are grown by metal organic vapor phase epitaxy on GaN/Al_2O_3 template. Second, micro-openings are created via optical lithography and chlorine-base etching. Third, thermal etching of GaN is performed under H_2 and NH_3 pulses. Optical microscopy, scanning electron microscopy, X-ray diffraction and atomic force microscopy are used to monitor lateral etching of GaN, bending of AlGaN layers induced by strain relaxation, and surface roughness of the AlGaN layer, following various thermal etching conditions (e.g. temperature, time, NH_3 flow rate). Micro reflectivity is used to estimate the spatial homogeneity of the reflectivity, and to investigate the impact thereon of surface roughness and of AlGaN strain-release induced deformation. Key findings are: 1) high temperature induces non-uniform lateral etching of GaN, 2) high NH_3 flow induces surfaces modifications affecting the overall reflectivity, 3) long thermal etching cycles seem to favor bending of AlGaN layers, thus disrupting the AlGaN/air periodicity and degrading the reflectivity. The configuration of the hole array (i.e. diameter and pitch) with respect to the initial thickness of the AlGaN/GaN stack is also investigated and found to have a strong impact on strain relaxation and bending of AlGaN layers. Ultimately, we demonstrate an average 90% reflectivity over a 200 nm wide stop band for only 10 AlGaN/air pairs for various central positions.

Finally, we perform III-nitride regrowth on AlGaN/air DBRs as well as mechanical transfer of 2D materials in order to demonstrate their potential use in optoelectronic and photonic devices.

PC-Thu-P7 - Structural and electrical properties of AlGaN/GaN heterostructures grown on 2-degrees off-axis 4H-SiC epilayers

2. Physics and characterization

Fabrizio Roccaforte[1]
Giuseppe Greco[1], Corrado Bongiorno[1], Salvatore Di Franco[1], Patrick Fiorenza[1], Filippo Giannazzo[1], Marco Mauceri[2], Andrea Severino[3], Ferdinando Iucolano[3], Pawel Prystawko[4], Marcin Krysko[4], Mike Leszczynski[4]
[1] CNR-IMM, Catania, Italy
[2] ASM/LPE, Catania, Italy
[3] STMicroelectronics, Catania, Italy
[4] IHPP, Warsaw, Poland

Abstract text: AlGaN/GaN heterostructures are strategic materials for high-power and high frequency transistors. In this context, semi-insulating (SI) on-axis silicon carbide (4H-SiC) is the substrate of choice for the growth of these heterostructures for RF applications. A cost-effective alternative to the SI on-axis 4H-SiC substrates is to grow a thick resistive SiC epitaxial layer onto a cheap conductive substrate.

In this work, the properties of AlGaN/GaN heterostructures grown onto resistive 2°-off-axis 4H-SiC epitaxial layers are investigated, demonstrating the suitability for HEMTs fabrication with high field effect mobility. For this purpose, a 15.5 μm thick resistive n-type 4H-SiC epilayer ($N_D<10^{14}$ cm^{-3}), has been grown onto a 2°-off axis 4H-SiC(0001). Then, AlGaN/GaN heterostructures have been grown by MOCVD by using AlN nucleation layer.

XRD analysis revealed a good crystalline quality of the AlGaN/GaN heterostructures, having a smooth surface (RMS=6.4 nm from a 5×5 μm^2 AFM scan). The 2DEG density, determined by C-V analyses on appropriate test-patterns, was on average 9.4×10^{12} cm^{-2}. The presence of dislocations in the GaN and AlGaN layer was observed by different techniques. In particular, plan-view TEM enabled distinguishing different dislocation features (edge, screw or mixed) and quantify their density (1.4×10^{9} cm^{-2}). The conductivity of the dislocations has been visualized by correlating AFM and C-AFM analyses, which confirmed the density measured by TEM. Then, TLM structures with Ti/Al/Ni/Au contacts, fabricated on two perpendicular relevant orientations of the off-axis 4H-SiC substrate, demonstrated the isotropy of the electrical properties, which is not always guaranteed in the off-axis grown. Test HEMTs devices (gate length 2mm) exhibited a g_{m_peak} = 41mS/mm and a V_{TH} = -4.5 V. To gain information on the carrier transport properties in these heterostructures, FATFETs were fabricated to correctly extract the channel mobility value. Both the field effect (μ_{FE}) and effective (μ_{eff}) mobility have been measured at different temperatures, considering the impact of the access region resistance and the temperature behavior of sheet and contact resistance. The decreasing temperature dependence of the channel mobility provided information on the major scattering mechanisms, paving the way for a future optimization of these systems.

PC-Thu-P8 - Temperature Dependence of the Optical Polarization Degree in AlGaN-Based MQWs with Emission Wavelengths in the Range of 220–230 nm

2. Physics and characterization

Hideaki Murotani[1]
Kaichi Tani[2], Shunsuke Ochiai[2], Yuhi Muragaki[2], Satoshi Kurai[2], Narihito Okada[2], Muhammad Ajmal Khan[3], Hideki Hirayama[3], Yoichi Yamada[2]
[1] National Institute of Technology, Tokuyama College, Shunan, Japan
[2] Yamaguchi University, Ube, Japan
[3] RIKEN, Wako, Japan

Abstract text: AlGaN multiple quantum wells (MQWs) have garnered significant attention as active layers in deep-UV light-emitting devices, such as light-emitting diodes and laser diodes. A key property of AlGaN MQWs is that the optical polarization of band-edge emission depends on the Al composition, lattice strain, and well thickness [1]. Since optical polarization directly affects light extraction, understanding its behavior is crucial for improving the performance of AlGaN-based deep-UV devices.
In this study, we investigated the temperature dependence of the optical polarization degree in AlGaN MQWs with emission wavelengths in the range of 220–230 nm using polarization-dependent photoluminescence (PL) spectroscopy.
The samples were grown by metalorganic vapor phase epitaxy on sapphire substrates, following the deposition of an AlN layer and an n-AlGaN layer. The MQW structures consisted of four periods of 6 nm-thick AlGaN wells separated by 1 nm-thick AlGaN barriers. Two samples were prepared with emission peaks at 220 nm (Sample 225) and 230 nm (Sample 230).
Polarization-dependent PL spectroscopy revealed that, for both samples, the luminescence intensity with an electric field perpendicular to the c-axis (E⊥c) was higher than that with an electric field parallel to the c-axis (E||c), indicating that the topmost valence band is the crystal-field split-off hole (CH) band. The optical polarization degree, defined as $\rho = (I_{\perp} - I_{\parallel}) / (I_{\perp} + I_{\parallel})$, where $I_{\perp}$ and $I_{\parallel}$ are the luminescence intensities for E⊥c and E||c, respectively, was $\rho = -0.76$ for Sample 225 and $\rho = -0.49$ for Sample 230 at 10 K, decreasing to $\rho = -0.40$ for Sample 225 and $\rho = -0.17$ for Sample 230 at 295 K. This reduction in the absolute value of the polarization degree with increasing temperature suggests a redistribution of holes among the valence bands.
Fitting analysis of the temperature dependence of the polarization degree, based on a Boltzmann distribution model of hole populations [2], estimated the energy separation between the CH and heavy hole (HH) bands to be 11 meV for Sample 225 and 6 meV for Sample 230. This is consistent with the observed trend that Sample 225 exhibits a greater absolute polarization degree than Sample 230.

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PC-Thu-P9 - Effects of Compositional and Interfacial Fluctuations on the Broadening of Excitonic Transition Linewidths in AlGaN-Based Quantum Wells

2. Physics and characterization

Hideaki Murotani[1]
Yoichi Yamada[2]
[1] National Institute of Technology, Tokuyama College, Shunan, Japan
[2] Yamaguchi University, Ube, Japan

Abstract text: The broadening of excitonic transition linewidths significantly affects luminescence properties and optical gain formation in semiconductors and quantum structures. Excitonic linewidth broadening in alloy semiconductors arises from statistical composition fluctuations within the exciton volume, known as the alloy broadening effect. This effect is particularly pronounced in AlGaN, where the exciton Bohr radius is relatively small [1]. In AlGaN quantum wells (QWs), linewidth broadening is influenced not only by alloy broadening but also by interfacial fluctuations and internal electric fields. However, few studies have comprehensively examined the combined effects of compositional and interfacial fluctuations, along with internal electric fields, on excitonic linewidth broadening in AlGaN QWs.

In this study, we theoretically investigated these effects. Our calculations focused on AlGaN/AlN QWs coherently grown on AlN substrates. The exciton linewidth was evaluated based on compositional and interfacial fluctuations within the exciton volume, estimated using variational calculations while accounting for internal electric fields within the $\boldsymbol{k \cdot p}$ perturbation framework.

First, we examined compositional fluctuations. The linewidth initially increased and then decreased with increasing Ga composition in the well, reflecting the alloy broadening effect. Additionally, the linewidth decreased with increasing well width due to exciton volume expansion. These results indicate that compositional fluctuations more strongly affect excitonic linewidth broadening in thinner QWs.

Next, we analyzed interfacial fluctuations. Their influence on excitonic linewidth broadening decreased with increasing well width. When the minimum lateral size of concave or convex regions at the interface was less than one-tenth of the exciton's lateral extent, their contribution to linewidth broadening was minor compared to compositional fluctuations. However, when this threshold was exceeded, interfacial fluctuations became a significant factor in linewidth broadening.

These findings highlight that both compositional and interfacial fluctuations exert a stronger influence on excitonic linewidth broadening in thinner well layers.

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PC-Thu-P10 - Degree of optical polarization and Urbach tails in (Al,Ga)N quantum wells: An atomistic tight-binding study

2. Physics and characterization
Robert Finn[1]
Michael O'Donovan[2], Thomas Koprucki[2], **Stefan Schulz**[1]
[1] Tyndall National Institute, Cork, Ireland
[2] WIAS, Berlin, Germany

Abstract text: Due to their large direct band gap, Aluminium Gallium Nitride (Al,Ga)N alloys have attracted significant attention for light-emitting applications in the ultraviolet (UV) part of the electromagnetic spectrum [1]. However, at UV-C wavelengths (<280 nm), (Al,Ga)N light emitters suffer from low quantum efficiencies, in part due to light polarization characteristics [1].

The symmetry of the highest valence band states differs between AlN and GaN giving rise to the emission of transverse magnetic (TM) and transverse electric (TE) polarized photons respectively [2]. TE polarized light leads to in general a higher light extraction efficiency, and is thus desirable in (Al,Ga)N-based light emitters. The relative emission of TM and TE polarized light is described by the degree of optical polarization (DOP), which depends on the orbital character of the hole states contributing to the light emission process. Alloy disorder in (Al,Ga)N can lead to valence band mixing effects and as such affect the DOP. We provide insight into the impact of disorder on the electronic structure and the DOP in (Al,Ga)N quantum wells (QWs) using a multi-band atomistic tight-binding model which accounts for alloy disorder on an atomistic level [3].

In particular, we study 1 nm, 2 nm and 3 nm QWs composed of $Al_{0.48}Ga_{0.52}N/Al_{0.63}Ga_{0.37}N$ and $Al_{0.75}Ga_{0.25}N/Al_{0.9}Ga_{0.1}N$ [4]. We investigate the impact that changing the composition, well width, and carrier screening has on tail states and the DOP. Carrier densities in the range of 10^{18} to 10^{20} cm^{-3} are considered.

Our studies show that disorder leads to a broadening of the hole density of states. This is described by an Urbach tail – an exponential decay in the density of states. The length of the tail decreases with increased screening, showing that localization effects are connected to the electrostatic built-in field [4]. In the $Al_{0.48}Ga_{0.52}N$ QWs the DOP is dominated by TE polarized light, however in the $Al_{0.75}Ga_{0.25}N$ QWs TM emission is much stronger. Additionally, carrier screening and well width impact the DOP and our results indicate that wider wells are beneficial for shifting the emission to TE polarization [4].

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PC-Thu-P11* - Optically Driven Ultrafast GHz-THz Coherent Acoustic Phonons in AlGaN/GaN heterostructures Under High-Excitation Densities

2. Physics and characterization

Shazan Ahmad Bhat[1]
Swaroop Ganguly[1], Dipankar Saha[1]
[1] Applied Quantum Mechanics Lab, Indian Institute of Technology, Bombay, India

Abstract text: We have demonstrated the manipulation of Coherent Acoustic Phonons (CAPs) and the impact of high excitation densities in AlGaN/GaN
heterostructures under ultrafast near-bandgap excitation at the Γ-transition point. Separate experiments were conducted on bare Gallium Nitride (GaN) and AlGaN/GaN heterostructures. Displacively excited coherent acoustic phonons induce a strain-modulated piezoelectric field which modulates the transmission of the probe beam via bulk Franz-Keldysh effect, observed as a phase flip with probe photon energy corresponding to the intrinsic bandgap. A large initial amplitude of CAP is observed in GaN, followed by faster decay due to screening of the piezoelectric field. In heterostructure, the strong piezoelectric field due to AlGaN/AlN enhances the coupling between coherent acoustic phonons and the piezoelectric potential. This coupling facilitates the excitation of long-lived, high amplitude cosinusoidal displacive coherent acoustic oscillations, which persist due to the interplay between strain waves, piezo-electric field modulation, and deformation potential coupling. We observe phonon frequencies between 40-80 GHz controlled by transit time and pump wavelength, and Brillouin frequency components around 100-120 GHz, with a large decay time. At higher excitation densities, we observe exotic effects in differential spectra as broadening, red shifts due to band-gap renormalisation and higher order effects due to carrier-induced screening and Pauli blocking, marking the transition into the threshold excitation regime. Near this regime, coupled phonon oscillations are observed as a beating pattern with frequency content beyond 1THz. These experimental conditions are equivalent to high field transport in the electrical operation regime, where the carrier excitation mechanism differs but energy release to the phonon sub-system is similar to optical excitation. Therefore, this study uniquely contributes to the development of on-demand coherent phonon sources without any superlattice structure and opens up possiblity for understanding plasmon-phonon interactions in AlGaN/GaN heterostructures for high-power solid-state applications.

PC-Thu-P12 - Thermal-Based Measurement Method of Effective Internal Optical Power and Internal Quantum Efficiency for Ultra-Violet AlGaN/GaN Light-Emitting Diodes

2. Physics and characterization

Byongjin Ma[1]
Taehee Jung[1], Kwanhun Lee[1]
[1] Korea Electronics Technology Institute, Seongnam-si, South Korea

Abstract text: AlGaN/GaN UV LEDs are widely used in many applications such as sterilization, curing and medical purposes, etc. The Reliability of UV AlGaN/GaN LEDs are defined by the degradation of an optical power [1]. However, it is very difficult to measure the optical power and internal quantum efficiency (IQE) accurately at deep ultra-violet wavelength region because of no highly sensitive detector. Conventional IQE measurement methods are based on the electrical and the optical properties under limited measurement conditions such as an extremely low temperature and a low current density of the LED chips. Furthermore, several assumptions are needed to obtain the absolute values of the IQE [3].

In order to overcome these problems, we propose a new measurement method for the effective internal optical power (IOP) and IQE, which uses a junction temperature measurement as a thermal property in addition to the electrical and optical properties. The basic concept of our model is that a ratio of the IOP is proportional to a ratio of the heat dissipation change at different conditions. And the heat dissipation change is also can be related to the change of the junction temperature (K) through a thermal resistance (K/W).

This method features normal operation condition and normal environment condition unlike the conventional methods [2-3]. And it has no need of absolute value of the optical power. Measured relative values of the optical power and the absolute value of the junction temperature, as shown in Fig. 1 and Fig.2, are enough to extract the value of alpha, defined as a ratio of thermal power to optical power, and to extract the IQEs as shown in Fig. 3 and Fig. 4. For a feasibility of our model, we have used InGaN/GaN LEDs in the moment, this method can also be used for UV AlGaN/GaN LEDs or InGaAs/GaAs infra-red LEDs.

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PC-Thu-P13 - Minimising plasma-induced damage on nGaN for uLED mesa etching applications

2. Physics and characterization

Sungjin Cho[1]
Zhengfei Wei[1], Andrew Newton[1], Stuart Robertson[2]
[1] Oxford Instruments Plasma Technology, Bristol BS35 4GG, United Kingdom
[2] Loughborough Materials Characterisation Centre, Department of Materials, Loughborough University, Loughborough LE11 3TU, United Kingdom

Abstract text: Micro Light Emitting Diodes (μLEDs) are considered the next-generation display technology, particularly for applications in wearable devices such as smartwatches, virtual reality, and augmented reality. To achieve high-resolution and high-brightness displays, smaller μLED dimensions are required. However, as the size of μLEDs decreases, the effect of the mesa sidewalls becomes more significant, leading to size-dependent leakage current density and reduced external quantum efficiency [1]. Mesa etching on GaN plays a critical role in device fabrication by isolating the active regions. Traditional mesa etching is typically performed using the Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) process, which introduces sidewall damage due to ion bombardment and ultraviolet photon irradiation. To mitigate this damage, post-wet treatments using TMAH and KOH have been reported [2]. In this abstract, we present the impact of ICP-RIE etching with optimised bias power on minimising sidewall damage while improving etch rate.

1.5 μm Si-doped (~1.5×10^{18} cm^{-3}) GaN, grown on sapphire substrates by metal-organic chemical vapour deposition, was etched using a standard mesa process with μLED masks. The etch rate in the optimised process, 50 nm/min, was competitive to present a realistic throughput for an LED manufacturing step. Photoluminescence (PL) measurements showed a 97.3% decrease in PL intensity for the standard mesa process compared to the unetched sample, whereas the optimised mesa etch process resulted in only a 31.8% decrease. Furthermore, Cathodoluminescence (CL) measurements revealed a 79.6% reduction in intensity for the standard mesa process, while the optimised process showed a much lower reduction of 15.7%. These results suggest that minimising ion bombardment during the mesa etching process can significantly reduce sidewall damage.

Future work will focus on investigating the impact of the low-damage mesa etch process on the performance of fully fabricated μLED devices.

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PC-Thu-P14* - Measuring spectral radiant flux from red InGaN MicroLEDs and calculating their external quantum efficiency – Pitfalls and possibilities

2. Physics and characterization
Anton Drott[1]
Martin Berg[2], Vanya DARAKCHIEVA[3]
[1] Division of Solid State Physics, Department of Physics, Lund University, Sweden & Alps Alpine Europe GmbH – Sweden Filial, Västra Frölunda, Sweden
[2] Hexagem AB, Lund, Sweden
[3] Lund University, Sweden

Abstract text: Microscopic light emitting diodes (MicroLED) hold the promise to revolutionize the display industry and make contemporary technologies obsolete due to their brightness and reliability. If they are still efficient that is. External Quantum Efficiency (EQE) can be calculated from the spectral radiant flux and the electrical current and it essentially describes how a device is able to convert electrons into photons that *escape the device*. It is therefore an important metric for comparing the performance of different devices. Measuring the spectral radiant flux from such small structures have proven to be a challenge in its own, in addition to the actual growth and processing.

MicroLED is orders of magnitude brighter than OLED and LCD and the dies can therefore be miniaturized to the sub-micron scale while still producing sufficient luminous flux. The early enthusiasm has cooled down somewhat when it became apparent that efficiency drops sharply below the ~50μm scale. This is especially true for red LEDs that are traditionally grown from phosphides or arsenides. Some research groups have turned their complete focus to InGaN instead which has shorter diffusion length but requires unprecedented Indium-composition for green and red emission. The prospect to use a single material system, i.e. InGaN, offers massive benefits when displays are to be produced in the millions.

A common way to measure spectral radiant flux is to mount the sample at the port of an integrating sphere where the emitted light is collected, homogenized through numerous reflections, and distributed evenly across its interior surface. A photodiode or spectroradiometer can then be used to probe the irradiance, from which the incident flux can be calculated.

A key challenge though, is that the flux produced by an InGaN microLED is very small, so each part of the system must be optimized for signal strength. Otherwise, the integration times and accumulated noise will corrupt either the results, the device or both. This work presents the design and implementation of a complete EQE measurement system. The impact of spectrometer type, opening slit, optical fiber types was examined, as well as temporal & spatial filtering techniques to mitigate thermal- and measurement noise. At the end, the typical procedures and importance of system calibration is discussed.

PC-Thu-P15* - Photoluminescence-based optical inspection for GaN / InGaN MicroLED wafers

2. Physics and characterization

Sami Dzsaber[1]
Ádám Virovecz[1], Zsolt Szekrényes[1], György Nádudvari[1]
[1] Semilab Co. Ltd., Budapest, Hungary

Abstract text: The advent of direct band gap semiconductors with large band gaps has led to a paradigm shift in the design and fabrication of modern, solid-state-based light-emitting devices operating in the visible portion of the electromagnetic spectrum. With the drive for ever-decreasing device size, GaN/InGaN LEDs of 1-10 micrometer characteristic dimension (MicroLEDs) are one step away from mass volume production, putting forward a high demand for fast and accurate inspection metrologies for product characterization.

Here, in line with these requirements, we present a fast and high spatial- and spectral resolution photoluminescence-based optical imaging and inspection tool, capable of simultaneously reporting the light-emission intensities and spectral peak wavelengths of all μLEDs on a fully-scanned wafer. We demonstrate a high spatial-resolution down to 0.5 micrometer/pixel, an emission peak wavelength accuracy below 2 nm, and a robust, single-device-segmentation-based image analysis protocol

PC-Thu-P16* - Competition between intrinsic and defective luminescence in GaN microdisks under nanoindentation

2. Physics and characterization

Zhiwei Si[1]
Zongliang Liu[2], Zhengqian Lu[3], Xiaoming Dong[3], Kebei Chen[3], Mengya Li[2], Xiaohui Peng[3], Tao Zhang[3], Jiafan Chen[3], Jianfeng Wang[3], Ke Xu[3]
[1] Information Materials Research Department, Suzhou Laboratory, Suzhou 215123, Jiangsu, China
[2] Shenyang National Laboratory for Materials Science, Jiangsu Institute of Advanced Semiconductors, Suzhou 215123, Jiangsu, China
[3] Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, Suzhou 215123, Jiangsu, China

Abstract text: The results on the introduction of defects by nanoindentation are limited to the study of dislocations, however, there is still a gap in the study of point defects under the action of nanoindentation. In the work, nanoscale mechanical properties of Na-flux GaN microdisks are investigated, which fills in the gap of the study of nanoindentation in GaN grown by the Na-flux method. This work reveals that GaN microdisks grown by the Na-flux growth method are capable of producing dislocation-induced rosette-like cathodoluminescence patterns (dislocation rosette) consistent with GaN obtained by other growth methods. The effect of indentation on the spatial distribution of intrinsic luminescence (i.e., band-edge luminescence (NBE)) and defective luminescence (i.e., green luminescence (GL)) and the competition between the two luminescence behaviors was investigated in detail, and it was found that both NBE and GL were reduced in the center of the indentation, and the band-edge normalized green luminescence was significantly enhanced at the edge of the indentation in terms of the GL intensity relative to the NBE intensity. Thus, there is a difference in the effect of non-radiative recombination centers, i.e., dislocations, generated by nanoindentation on NBE and GL. This may be due to the fact that the dislocations introduce a large number of point defects (gallium vacancies, etc.), and the gallium vacancies contribute to the defect luminescence (DL), resulting in a non-equal reduction in the NBE and GL luminescence intensities. In addition, there is also a significant competition between NBE and DL luminescence with increasing depth, the relative intensity of NBE decreases, and the defect luminescence is gradually red-shifted with increasing depth, which may be attributed to the introduction of a large number of dislocations decorating a large number of gallium vacancies at the tip of the indentation resulting in the predominance of the yellow luminescence of the DL. This work enriches the scope of nanomechanical studies of GaN and expands the study of the spectral range of GaN under nanoindentation.

PC-Thu-P17* - The fingerprints of ultra-thin shells on GaN nanowires in macroscale performance

2. Physics and characterization

Radoslaw Szymon[1]
Eunika Zielony[1], Marta Sobanska[2], Tomasz Stachurski[3], Anna Reszka[2], Aleksandra Wierzbicka[2], Sylwia Gieraltowska[2], Sara Piotrowska[2], Tomasz Plocinski[4], Zbigniew Zytkiewicz[2]
[1] Wroclaw University of Science and Technology, Department of Experimental Physics, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
[2] Institute of Physics, Polish Academy of Sciences, Al. Lotnikow 32/46, 02-668 Warsaw, Poland
[3] University of Economics in Katowice, Department of Statistics, Econometrics and Mathematics, 1 Maja 50, 40-287 Katowice, Poland
[4] Warsaw University of Technology, Faculty of Materials Science and Engineering, 02-507 Warsaw, Poland

Abstract text: Gallium nitride nanowires pose new opportunities for optoelectronic applications due to their low crystal lattice strain, excellent structural quality, and quantum confinement effects. However, their large surface area leads to formation of surface states, band bending, and high sensitivity to external conditions, quenching luminescence efficiency. To mitigate these effects, post-growth surface passivation is essential. The atomic layer deposition (ALD) of oxide shells, such as AlO_x and HfO_x, has been proposed as an effective strategy to enhance nanowires performance by passivating surface states, reducing band bending, and protecting against environmental degradation.[1,2]

This study of the core-shell GaN-oxide nanowires grown by molecular beam epitaxy shows that the influence of ultra-thin shells (≤ 5 nm) on properties of the nanowires turns out to be nontrivial and crucial. Scanning (SEM) and transmission electron microscopy (TEM) indicated an island growth mode of such shells. This morphological feature clearly affects the structural and optical properties of the nanowires. X-ray diffraction (XRD) and Raman spectroscopy confirmed a reduction in their crystal lattice strain, while photoluminescence (PL) and cathodoluminescence (CL) measurements showed substantial enhancement in luminescence intensity. Finally, the luminescence stability under varying external conditions was evaluated to determine the optimal shell thickness for effective nanowire passivation.

Our findings emphasize the critical role of surface engineering in optimizing the performance of GaN nanowire-based optoelectronic devices such as nano-LEDs and photodetectors. The results highlight that achieving desirable properties requires development of the shell deposition process, encourage the investigation of other material systems, and motivates further research to provide deeper insights into the mechanisms governing luminescence quenching and enhancement.

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PC-Thu-P18 - High-Piezoelectric properties of GaN Nanowires for Powering Medical Implants

2. Physics and characterization

Szu-Wei Chen[1]
Quang Chieu Biu[1], Amaury Chevillard[1], Laurent Travers[1], Teo Baptiste[1], Maria Tchernycheva[1], Ann-lenaig Hamon[2], Noëlle Gogneau[1]
[1] Center de Nanosciences et de Nanotechnologie (C2N), Université paris-Saclay/Université Paris-Cité/CNRS, UMR9001, 10 Boulevard Thomas Gobert, 91120 Palaiseau, France
[2] Laboratoire de Mécanique Paris-Saclay(LMPS), CNRS UMR 8579, CentraleSupélec, Université Paris-Saclay, 3 rue Joliot-Curie, Gif-sur-Yvette Cedex, 91192 France

Abstract text: The new generation of pacemakers is strongly reduced in size (few centimeters long, few millimeters large) in comparison with the actual implanted ones. The development of ultra-compact and high-efficient generator is required for replacing the time limited micro-batteries.

These last decades, GaN appears as a suitable material for piezoelectric applications. Synthesized under nanowire (NW) form, GaN is characterized by four main properties allowing to fundamentally improved its electromechanical conversion efficiency: thanks to their large aspect ratio and quasi-perfect crystalline quality, NWs are characterized by superior mechanical properties and enhanced flexibility conferring them the potentiality to be deformed under small applied force without fracture; due to their nanometer scale dimensions, GaN NWs present enhanced piezoelectric coefficients in comparison with 2D films ; and finally, for 100 nm wide GaN NWs, the surface charges effects become an advantage by engineering properly the NW dimensions and/or environment.

GaN NWs have demonstrated their efficient conversion capacity of a mechanical deformation into an electrical energy, then opening the way for powering micro-devices. Combined with their biocompatible character, these nanostructures appear as the perfect candidate for powering medical implants like pacemakers.

Currently, transducers based on 1D nanostructures can generate power from nW/cm² to µW/cm², approaching the pacemaker energy needs. However, this active layer must be able to be activated under heartbeats. To ensure this operation under the best conditions and thus maximizing the power capacity of the GaN NW based piezo-nanogenerator, we integrate it into a Silicon-MEMs structure ensuring the adequation between the heartbeats frequency and the optimum generator working frequency. The deformation of the active transducer, controlled by the MEMs, has been calculated based on the mechanical properties of Silicon.

In this work, we characterize the piezoelectric response of the Ga(In)N NW transductor mimicking the imposed MEMs deformation. We investigate different configurations of the NWs, such as the integration of InGaN insertion in the GaN NWs volume or the NW surface treatment for enhancing the surface charge effects, two ways known for improving the electromechanical properties of GaN NWs.

PC-Thu-P19* - Investigation of InGaN/GaN nanowire oxidation for functionalization and size-tuning of the quantum discs

2. Physics and characterization

Nidel Dilan TCHOULAYEU POSSIE[1]
Krishnendu Sarkar[1], Quang chieu Bui[1], Amel Zorai[1], Roberto Hernandez[1], François Maillard[1], Ludovic Largeau[1], Julien Chaste[1], Laurent Travers[1], Martina Morassi[1], Stefano Pirotta[1], Francois Julien[1], Jean-christophe Harmand[1], Maria Tchernycheva[1], Noelle Gogneau[1]
[1] Centre de Nanosciences et Nanotechnologies, Paris-Saclay University, Palaiseau, France

Abstract text: InGaN/GaN quantum discs (QDs) embedded in nanowires (NWs) are interesting for applications such as red LEDs or hydrogen generation. NWs are free from dislocations and allow easier stress relaxation through their free lateral surface. However, high surface to volume ratio results in high sensitivity of the NW properties to surface phenomena, which need to be controlled.

In this contribution, we focus on the thermal oxidation as a way to control and functionalize the NW surface. We describe the growth of InGaN/GaN NWs on Si (111) by Plasma-assisted molecular beam epitaxy (PA-MBE) and their transformation into nitride/oxide core/shell NWs by post-growth oxidation. The oxide shell has a catalytic activity which can be used for hydrogen generation. Moreover, the oxidation allows to reduce the lateral size of the InGaN QDs initially determined by the NW epitaxy as a way to tune their emission wavelength. Previously, we have developed the post-growth thermal oxidation strategy for GaN NWs, in a temperature range of [800°C - 950°C] where Ga_2O_3 shell surrounding GaN core is achieved with a thickness up to 14 nm. Here we adapt this oxidation process for InGaN/GaN NWs where the challenge is to work at lower temperature in order to avoid damaging the InGaN QDs. In particular, we developed the oxidation of InGaN/GaN NWs to obtain a shell of Ga_2O_3/In_2O_3 of a controlled thickness by adjusting the oxidation parameters (temperature, oxidation time, O_2/N_2 flux ratio). For LED application, the formation of this oxide shell has a double impact on the QD characteristics. First, since part of the Ga(In)N is decomposed and transformed into Ga2(In2)O3, the QD size is reduced leading to higher lateral confinement. Second, the presence of the shell induces a lateral strain (depending on the core-shell thickness ratio) then creating an internal strain in the QD and shifting its emission. For H_2 generation, the Ga_2O_3/In_2O_3 shell increases the surface reaction, while the InGaN insertion allows a photocatalytic activation under sunlight. The structural properties of the core/shell NW structures are investigated by combining XRD, TEM-STEM and EDX. The optical response of the InGaN/$Ga_2(In_2)O_3$ core-shell NWs oxidized under different conditions is analyzed by cathodoluminescence. We show that the InGaN emission is preserved after oxidation while its energy is modified.

PC-Thu-P20* - Enhancement of Electron Injection in GaN-on-Si Nanowire-Based Vertical Devices Using a Graphene Buffer

2. Physics and characterization

Swagata Bhunia[1]
Yang Li[1], Tron Arne Nilsen[1], Gulzhan Baigarinova[1], Bjørn-Ove Fimland[1], Helge Weman[1]
[1] Department of Electronic Systems, Norwegian University of Science and Technology (NTNU), NO-7491, Trondheim, Norway

Abstract text: Over the past two decades, GaN nanowires (NWs) have emerged as promising candidates for the next generation optoelectronic and electronic devices, such as light emitting diodes, laser diodes, photodetectors and transistors [1]. If GaN NWs are grown on doped Si substrates, the substrate can serve as a bottom contact for NW-based devices. However, their performance is hindered by a ~ 2-3 nm thick amorphous silicon nitride (Si_xN_y) interlayer forming at the GaN NW/Si substrate interface [2]. A promising alternative is to use graphene as a buffer layer, as it may prevent the formation of the Si_xN_y layer as well as reduce the formation of any lattice-mismatch induced defect states at the NW/substrate interface due to van der Waals epitaxy [3]. While GaN NWs have been successfully grown on graphene/Si substrates, their impact on NW-based devices has yet to be explored. In this work, we have grown GaN NWs on graphene/n^{++}-Si and n^{++}-Si substrates using molecular beam epitaxy (MBE) and fabricated vertical devices for I-V characterization.

A 1 cm^2 piece of graphene grown by chemical vapor deposition was first transferred to a SiO_2-etched 2-inch n^{++}-Si(111) wafer. The GaN NWs were then grown by MBE following a two-step growth method: nucleation at 720˚C followed by NW growth at 750˚C. Devices were fabricated by defining a 1 mm^2 square pattern using photolithography and depositing Ti/Au (20 nm/200 nm) on top of the NWs and on the backside of the n^{++}-Si wafer using e-beam evaporation. For comparison, devices were fabricated on graphene/Si and Si areas on the same wafer. Scanning electron microscopy images show a high density of vertical NWs on the graphene/Si region and transmission electron microscopy images reveal crystalline GaN NWs with a ~ 1 nm Ga_xO_y interlayer (in contrast to ~ 2 nm amorphous Si_xN_y in the region without graphene) between the Si substrate and the GaN NW. The I-V characteristics of fabricated devices, show a significant improvement in the current density and a reduction in turn-on voltage for NWs grown on graphene/Si, compared to those grown directly on Si, which may be attributed to a lower barrier height induced by the graphene buffer.

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PC-Thu-P21 - Raman spectroscopy applied to measurement of Mg doping in GaN nanostructures

2. Physics and characterization

Kris Bertness[1]
Matt Brubaker[1], J. Andrew McArthur[1]
[1] Applied Physics Division, NIST, Boulder, Colorado, United States

Abstract text: We apply Raman spectroscopy to estimate Mg incorporation in a variety of GaN nanostructures grown by molecular beam epitaxy (MBE), including core-shell nanowires, nanofins, and axial p-/p+ nanowires. The peak areas of the local vibrational mode of Mg atoms located on a Ga site are normalized to the main GaN Raman peak areas to estimate the concentration of Mg atoms that can provide holes when ionized. By comparison with SIMS and Hall effect carrier concentration measurements on planar films, we estimate that the normalized Mg signal is about 0.08 for active Mg concentration of $4x10^{19}$ cm^{-3}. By comparing the normalized Mg Raman for various growth conditions and morphologies, we see that efficient incorporation of Mg requires low growth temperature (ideally below 750 °C) and high V:III ratio. Because temperatures > 800 °C are needed for selective area growth in MBE, this temperature dependence effectively limits addition of p-type material to either shells grown after an n-type core defines the geometry or to axial extensions in tightly spaced structures where shadowing will prevent growth on the sidewalls. However, nanostructure growth can utilize very high V:III ratios, and the strongest Mg signals were measured for nanostructures. We also carried out temperature-dependent electrical measurements on several core-shell nanowires from two separate runs where the outer shell was heavily doped. Although the I-V curves indicate that the contacts were Schottky-like, we obtained reasonable results when the electrical data was analyzed with a simple model that attributes change in dynamic resistance with changing temperature at constant current to change in free hole concentration in the shell. For a run with a thin shell (80 nm), the activation energy of the Mg was extracted to be 110 meV +/- 20 meV. For a run with a thicker shell (350 nm), the activation energy varied from 60 meV to 110 meV with increasing current, which we tentatively interpret to indicate that the shell is more heavily doped in the outer layers. These activation energies reproduce data in the literature that show a decrease in activation energy as the Mg concentration increases.

PC-Thu-P22* - Lasing Dynamics of One-dimensional Core-shell GaN/InGaN Nanowire Structures with Ultra-low Thresholds

2. Physics and characterization

Dae-Young Um[1]
Jeong-Kyun Oh[1], Sung-Un Kim[1], Min-Seok Lee[1], Cheul-Ro Lee[1], Yong-Ho Ra[1]
[1] Division of Advanced Materials Engineering, Engineering College, Research Center for Advanced Materials Development (RCAMD), Jeonbuk National University (JBNU), Jeonju 54896, Republic of Korea.

Abstract text: With the increasing demand for efficient and compact coherent light sources in VR/AR/XR technologies, the development of on-chip ultracompact devices with extremely low lasing thresholds has become essential. Among various materials, low-dimensional semiconductors especially 1D GaN/InGaN heterostructures have gained significant attention for their ability to integrate complex three-dimensional structures seamlessly. In particular, 1D nanowires (NWs) based on uniaxial heterostructures have demonstrated potential for optically pumped lasing, attributed to the small gain volume of their uniaxial active region along the c-axis. Remarkably, these NWs can achieve lasing even without the need for auxiliary structures such as polarized media or periodic configurations. However, a major limitation arises due to the high surface recombination velocity in 1D GaN nanostructures, which results from their large surface-to-volume ratio and significantly restricts their overall device performance. In this work, we propose 1D coaxial heterostructure NWs with large gain mediums, enabling ultra-low threshold gain (g_{th}) under optical pumping at room temperature, thereby achieving continuous wave (CW) nanolaser operation. By optimizing the core-shell structure of GaN-based 1D NWs each extending beyond 10 μm in length we successfully obtained ultra-low lasing thresholds. This was accomplished through high optical gain, precisely controlled quantum well layers, and structural design optimization. In the proposed 1D NW system, the TE_{01} and HE_{21even} modes exhibited the lowest g_{th} values, measured at approximately 750 cm^{-1} and 870 cm^{-1}, respectively, at a blue wavelength of 451 nm. The lasing characteristics at 451 nm were comprehensively investigated using a power-dependent micro-photoluminescence (μ-PL) system, and further analyzed through the Ansys Lumerical finite-difference-time-domain (FDTD) simulations. Thus, the core-shell 1D UL-NW-based lasing system represents a highly efficient platform for achieving ultra-low lasing g_{th}, making it a promising candidate for nanoscale light sources.

PC-Thu-P23* - From Experiment to Equation a Predictive Model for Quantum Dot Photoluminescence

2. Physics and characterization

Kusumkoli De[1]
Dipanwita Aich[1], Tanushree Dey[1], Dipankar Saha[1], Swaroop Ganguly[1]
[1] Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai, India

Abstract text: Quantum dots (QDs) are emerging as key materials for optoelectronic and photonic applications due to their tunable photoluminescence (PL) properties. In determining the PL efficiency of QD material, there exists an interplay among QD density-induced non-radiative recombination, quantum confinement, and carrier recombination kinetics, which depend on several parameters such as QD size, density, and filling factor. Understanding and optimizing these parameters is essential for maximizing optical performance in QD-based devices. InGaN/GaN (QDs) have been proven to be extremely promising as efficient light emitters in the visible regime. In this study, we systematically analyze the PL intensity trends of three InGaN/GaN QD samples—Q1, Q2, and Q3—of varying QD sizes, density, and filling factor, through temperature-dependent PL (TDPL), power-dependent PL (PDPL) spectroscopy, and time-correlated single-photon counting (TCSPC) measurements.

Our PL measurements reveal that Q2 exhibits the highest PL intensity, despite Q3 having the highest QD density and size. PDPL analysis further confirms this trend, where Q2 maintains a γ (slope of the log-log plot of integrated PL intensity vs. excitation power) value of 1 across all temperatures, indicating dominant excitonic recombination with minimal non-radiative losses. In contrast, Q3, which exhibits the shortest amplitude-weighted PL lifetime in TCSPC, shows a significant drop in γ from 0.9 at 10K to 0.5 at 300K, confirming increased non-radiative recombination at elevated temperatures. Thermal stability analysis through TDPL further supports this, revealing that Q3 has a lower activation energy, indicative of shallow trap states or ineffective surface passivation. Anomalous behaviour in the full-width at half maximum (FWHM) is observed, where Q3, despite having the smallest QD size, exhibits a counterintuitive decrease in FWHM, suggesting strong carrier trapping that prevents redistribution and suppresses linewidth broadening. Q1, which has a broader FWHM, undergoes greater carrier thermalization and redistribution, consistent with its stable γ value of 0.9 in PDPL.

To validate these experimental observations, we develop an empirical model where a nonlinear fitting approach optimizes model parameters, revealing a power-law dependence on QD size and density, with additional influence from the filling factor.

PC-Thu-P24* - Nanoscopic Luminescence Analysis of GaN/AlN Quantum Dots

2. Physics and characterization

Gordon Schmidt[1]
Peter Veit[1], Frank Bertram[1], Jürgen Christen[1], Raphaël Butté[2], Nicolas Grandjean[2]
[1] Institute of Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, Germany
[2] Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Abstract text: Self-organized quantum dots (QDs) exhibit complex three-dimensional confinement potentials due to structural inhomogeneities and strain distribution. QD spectroscopy using highly spatially resolved cathodoluminescence (CL) in a scanning transmission electron microscope (STEM) provides direct insight into the energy structure of individual QDs, correlating optical properties with nanoscale morphology.

In this study, we present a nanoscopic exploration of luminescence from GaN/AlN QDs in a 10-fold layer stack using low temperature STEM-CL microscopy. The QD layer stack with 5 nm AlN barriers was grown by molecular beam epitaxy (MBE) on an MOVPE-AlN/sapphire template. During MBE growth, a temperature and growth rate gradient across the wafer leads to a variation in the QD size.

For STEM-CL investigations, lamellae were prepared from different wafer positions using a focused ion beam with subsequent Ar ion milling. Since the QDs vary in size, we observe a drastic blue shift of the ensemble emission wavelength, from $\lambda = 330$ nm at the wafer center to $\lambda = 265$ nm at the wafer edge, caused by a decrease in QD dimensions. At the wafer center, lateral thickness variations indicate distinct GaN QD formation, with QD height increasing from ~2.6 nm to ~5.6 nm from the bottom to the top layer. This alters the QD emission drastically in a way that the ensemble luminescence shifts by more than $\Delta\lambda = 20$ nm towards longer wavelengths. Furthermore, a coherent vertical stacking of QDs was locally observed, a signature of self-organized multilayer QD structures driven by surface strain fields favoring nucleation atop buried dots. In contrast, QDs at the wafer edge exhibit minimal height variations and show almost no spectral shift.

Leveraging the nanoscale resolution of STEM-CL, we performed single-dot spectroscopy, resolving emission from individual QDs. Highly spatially resolved spectral line scans provided direct visualization of vertical carrier/exciton transport into a single QD. A continuous spectral shift of more than 40 meV was observed as the electron beam approaches the QD position. This effect will be analyzed in context of the increase of the numbers of excess carriers reaching the dot.

PC-Thu-P25* - Investigation of GaN/AlN self-assembled quantum dots through time-resolved photoluminescence

2. Physics and characterization
Johann Stachurski[1]
Gordon Callsen[1], Sebastian Tamariz[1], Raphaël Butté[1], Nicolas Grandjean[1]
[1] Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

Abstract text: Room-temperature single-photon emission from GaN quantum dots (QDs) embedded in AlGaN nanowires has been successfully demonstrated over a decade [1]. More recently, we showed that self-assembled GaN QDs embedded in planar AlN epilayers grown on Si(111) also exhibit this capability, featuring bright emission and high single-photon purity [2]. Additionally, the integration of such emitters into bullseye structures for enhanced single-photon extraction efficiency has been demonstrated [3], further paving the way for room-temperature quantum photonic applications. Despite these early advancements, a comprehensive understanding of the carrier dynamics in GaN QDs remains elusive, hindering their progress toward engineering applications. In particular, the strong built-in fields in these polar structures significantly alter the interplay between excitonic states compared to their III-arsenide counterparts [4], leading to large fine structure and exciton-biexciton splittings.

Building upon the hybrid biexciton framework [5], we investigate how this distinctive carrier dynamics shapes the temperature-dependent optical signature of GaN/AlN QDs. We further present an exhaustive comparison of our time-resolved (TR) temperature- and power-dependent photoluminescence (PL) measurements with existing literature to highlight the influence of the substrate on QD dynamics. Finally, we analyze QD TRPL transients in the high-injection regime to elucidate the role of non-radiative recombination channels on the QD deexcitation.

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PC-Thu-P26* - Microscopic theory of phonon polaritons and long wavelength dielectric response

2. Physics and characterization
Olle Hellman[1]
Leeor Kronik[1]
[1] Department of Molecular Chemistry and Materials Science, Weizmann Institute of Science, Rehovoth 76100, Israel

Abstract text: We present a first-principles approach for calculating phonon-polariton dispersion relations. In this approach, phonon-photon interaction is described by quantization of a Hamiltonian that describes harmonic lattice vibrations coupled with the electromagnetic field inside the material. All Hamiltonian parameters are obtained from first-principles calculations, with diagonalization leading to non-interacting polariton quasiparticles. This method naturally includes retardation effects and resolves non-analytical behavior and ambiguities in phonon frequencies at the Brillouin zone center, especially in non-cubic and optically anisotropic materials. Furthermore, by incorporating higher-order terms in the Hamiltonian, we also account for quasiparticle interactions and spectral broadening. Specifically, we show how anharmonic effects in phonon polaritons lead to a dielectric response that challenges traditional models. The accuracy and consequences of the approach are demonstrated on GaP and GaN.

OD-Thu-P1* - High Efficiency and Large Current Injection AlGaN-based Deep Ultraviolet Micro-LED Arrays

3. Optical devices

Xuejiao Sun[1]
Yu Xie[2], Ming Feng Gong[2], Xuecheng Wei[1], Naixin Liu[1]
[1] Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
[2] School of Semiconductor and Physics, North University of China, Taiyuan, Shanxi 030051, China

Abstract text: AlGaN-based deep ultraviolet LEDs are widely used in air purification, healthcare, and water treatment, and have attracted significant attention. In recent years, DUV micro-LEDs, due to their high current density and short carrier lifetime, have emerged as the best candidates for enhancing modulation bandwidth, leading to frequent reports in the field of optical wireless communication. However, in most studies the light output power (LOP) of DUV micro-LEDs remains relatively low, typically below 1 mW, with wall-plug efficiency (WPE) less than 1%. These performance values are insufficient for meeting the demands of long-distance transmission.

The low light output power (LOP) and wall-plug efficiency (WPE) of DUV micro-LEDs are mainly attributed to material defects, insufficient light extraction efficiency, and thermal management limitations. The high dislocation density in the AlGaN-based epitaxial layer, combined with lattice mismatch between the sapphire/AlN substrate, significantly reduces the internal quantum efficiency (IQE). The high material absorption rate at ultraviolet short wavelengths and light loss in traditional device structures further diminish the light extraction efficiency. Additionally, current injection unevenness and thermal accumulation caused by high thermal resistance in miniaturized devices further restrict performance.

In this work, densely packed planar mesa arrays with the same mesa diameter of 25 μm, consisting of 4, 8, 16, and 32 mesas are designed. Compared with traditional commercial devices, the overall light emission efficiency of the arrays is enhanced benifiting of increasing the light emission from the sidewalls. This study explores the effect of varying the number of mesas on device performance for the same package size. Furthermore, segmented annealing is proposed to reduce the p-type and n-type ohmic contact resistivity. Finally, a dual-layer passivation structure is introduced, which not only incorporates a reflective design but also addresses the issue of crowded device packaging and alignment.

The device with 32 mesas demonstrates the best electrical and optical performance. The turn-on voltage is 4.32 V, operating at 30 mA with a voltage of 5.589 V and WPE of 5.03%. At a current density of 496 A/cm², the peak optical power reaches up to 13.5 mW.

OD-Thu-P2* - A path towards thin-film flip-chip UVC LEDs by photo-assisted electrochemical etching

3. Optical devices

Phuc T. Nguyen[1]
Artem Shushanian[1], Joachim Ciers[1], Åsa Haglund[1]
[1] Department of Microtechnology and Nanoscience, Chalmers University of Technology, 41296 Gothenburg, Sweden

Abstract text: Photo-assisted electrochemical etching (PECE) could potentially be used to selectively remove a sacrificial layer and lift off UVC LEDs. Challenges with this technology are the porosification of the doped LED structure and the strain relaxation during under-etching that can bend or crack the LED membrane, especially compressively strained UVC LEDs grown on an AlN substrate. Here, we demonstrate a way to hinder parasitic etching and membrane cracking by properly designing the etch block layer and protective dielectric coating on the top of the LED.

Underneath the 100x100 μm^2 UVC LEDs, we used a sacrificial layer composed of a superlattice with 5x($Al_{0.35}Ga_{0.65}N$/$Al_{0.55}Ga_{0.45}N$). Between them, there is an etch block layer to prevent the etching progressing vertically into the LED. High-bandgap AlN is ideal but strain-inefficient, so we compared two different etch block layers; a 600 nm $Al_{0.8}Ga_{0.2}N$ layer and a 300 nm AlN/300 nm $Al_{0.8}Ga_{0.2}N$. To improve the strain management of the under-etched membrane, two different dielectric top protection layers were used; a 500-nm thick compressively strained SiO_2 (144 MPa) and a lower compressively strained SiN_x film (40 MPa) of the same thickness, both deposited by plasma-enhanced chemical vapor deposition. We ran the PECE in a two-electrode setup in 3 mM HNO_3, with 23-mW/cm² 275-nm LED illumination through the substrate, starting at higher voltage and maintaining 7 V during under-etching.

All membranes from both samples with the SiO_2 protection layer cracked, while 89% of the SiN_x-covered membranes remained crack-free. PECE led to a small parasitic etching of the LEDs of about 3.1% for the SiO_2-covered samples and slightly higher (4.6%) for the $Al_{0.8}Ga_{0.2}N$ etch block and the SiN_x capping layer. However, samples with an $Al_{0.8}Ga_{0.2}N$ etch block layers show a porosification that is very localized near the initiation hole of the PECE, leaving most part of the center LED membrane intact. Photoluminescence of the QWs shows a red-shift of the PL-peak of 4-6 nm, i.e. indicating a relaxation of the strained membrane when under-etched.

In summary, we have here shown a pathway towards thin-film flip-chip UVC LEDs with electrochemical etching by using a 600-nm thick $Al_{0.8}Ga_{0.2}N$ etch block that provides a better localization of the parasitic etching, and a low-strained SiN_x that helps to prevent cracking of the membrane.

OD-Thu-P3 - High-efficiency air-cavity reflector for DUV micro-LEDs

3. Optical devices

Zhaoqiang Liu[1]
Zi-Hui Zhang[2], **Xiao Wei Sun**[1]
[1] Institute of Nanoscience and Applications, and Department of Electrical and Electronic Engineering, Southern University of Science and Technology, Shenzhen 518055, China
[2] School of Integrated Circuits, Guangdong University of Technology, 100 Waihuan West Road, Panyu District, Guangzhou City, Guangdong 510006, China

Abstract text: AlGaN-based deep ultraviolet light-emitting diodes (DUV LEDs) exhibit several notable advantages, including non-toxicity, environmental friendliness, long operational lifetime, and compact size. These characteristics make them highly suitable for a wide range of applications, such as optical communication, sterilization, medical diagnostics, and water purification. However, the relatively low light extraction efficiency (LEE) of DUV LEDs significantly limits their further application in fields such as UV communication and sterilization. The combination of an inclined sidewall structure with an omnidirectional reflector (ODR) exhibits significant potential for enhancing the LEE of DUV LEDs. However, the evanescent wave generated by total internal reflection (TIR) of transverse magnetic (TM) polarized light excites Al surface plasmon polaritons (SPPs), reducing the reflectivity of the Al-based ODR on the inclined sidewalls. For this purpose, we design and fabricate a DUV micro-LED array. A bottom air-cavity reflector is fabricated using a positive-negative photoresist stacking process to enhance the LEE of the device. The experimental results demonstrate that the DUV micro-LED array with an air-cavity reflector achieves a 9.88% improvement in optical power compared to the traditional DUV micro-LED array with a sidewall metal reflector. In addition, the optical characteristics are investigated using finite-difference time-domain (FDTD) simulations. Based on the optical field intensity distribution, the bottom air-cavity reflector strategy effectively reduces sidewall metal absorption and provides additional light escape paths, thereby enhancing the LEE of the DUV micro-LED array. The simulation of micro-LED size variations shows that the LEE of DUV micro-LED arrays increases with decreasing device size. For micro-LEDs with diameters of 30 μm and 5 μm, this strategy improves the LEE of TM (TE) modes by 56.82% (13.88%) and 74.64% (21.42%), respectively. Notably, the air-cavity reflector significantly enhances the LEE of smaller-sized devices. Therefore, this work provides a reliable method for fabricating high-output-power AlGaN-based DUV micro-LEDs.

OD-Thu-P4 - Wafer-scale characterization of 4232-Pixel-Per-Inch red micro-LED arrays for industrial mass production

3. Optical devices

Hyeong Ho Park[1]

[1] Convergence Technology Division, Korea Advanced Nano Fab Center (KANC), Suwon, Republic of Korea

Abstract text: Micro-light-emitting diode technology continues to attract strong interest due to the high resolutions, outstanding luminous efficiency, remarkable brightness, and impressive durability. Despite the advancements in micro-LED technologies, several issues hinder their widespread application. For example, the application of near-eye displays to industrial mass production requires comprehensive wafer-scale characterization of red micro-LED arrays. To the best of our knowledge, wafer-scale characterization of the red micro-LED arrays has not yet been reported in detail.

In this work, we fabricated various sizes of InGaN/GaN red micro-LEDs on a 4-inch Si substrate and analyzed the optical and electrical characteristics depending on the device size. Additionally, we demonstrated the high PPI passive display array and examined the feasibility of driving pixels using pulse-width modulation (PWM). For industrial mass production, uniformity in micro-LED pixel electrical parameters such as V_F characteristics is a very important factor for high quality displays. The V_F values of 120 pixels from region 1 to region 5 in the 4-inch wafer are 3.33, 3.34, 3.33, 3.54, and 3.67 V at 30 A/cm^2, respectively. The V_F variation of 120 pixels with 5 different regions is only 0.34 V (10.21 %) and the value is very low and narrow distribution in 4 inch wafer. This study pioneered the exploration of size-dependent characteristics of InGaN/GaN red micro-LEDs grown on 4-inch Si substrates and demonstrated the large-scale fabrication and operation of an ultra-high-resolution PPI binary image display at 4232 PPI. This high-performance red micro-LED arrays demonstration provides a promising and practical solution to realize micro-LED displays used in augmented reality (AR) and extended reality (XR) applications, circumventing the bottleneck in the development of long-lifespan and high-brightness organic LED devices.

OD-Thu-P5* - Optical gain measurements of InGaN red-light-emitting LED epitaxial layers

3. Optical devices

Itsuki Shimbo[1]
Atsushi A. Yamaguchi[1], Daisuke Iida[2], Kazuhiro Ohkawa[2]
[1] Optoelectronic Device System Research and Development Center, Kanazawa Institute of Technology, Nonoichi, Japan
[2] Energy Conversion Devices and Materials Laboratory, King Abdullah University of Science and Technology, Thuwal, Kingdom of Saudi Arabia

Abstract text: A red-light-emitting semiconductor laser using InGaN quantum well (QW) as an active layer has not been realized yet. The main cause can be the lattice mismatch between an InGaN active layer and underlying GaN layer, inducing the defect generation and piezoelectric field. In recent years, however, an InGaN red-light-emitting LED with strain compensation techniques has shown a relatively higher value of external quantum efficiency. In this study, we have tried to measure the optical gain in the red-light-emitting InGaN QW LED epitaxial layers by the variable stripe length method.

The LED epitaxial layers include a red InGaN QW on an unintentionally doped (uid) $In_{0.02}Ga_{0.98}N$ barrier layer, a blue InGaN QW for the strain compensation and 30 periods of $In_{0.08}Ga_{0.92}N$/GaN superlattices. Since these layer structures are not designed for lasers, the optical confinement factor (OCF) is very small. For the optical gain measurements, a Nd: YAG-THG laser (λ = 355 nm) was used as an excitation light source, and its stripe-shaped beam was irradiated to the sample in a cryostat (cooled to 3 K). The stripe length was changed from 200 mm to 2400 mm by using an adjustable-width slit.

In emission spectra under high excitation power density and long stripe length, two amplified-spontaneous-emission (ASE) peaks are observed that can be identified as from the uid-InGaN barrier layer and the blue InGaN QW. It is suggested that the carrier dynamics within the layered structure are not simple. Nevertheless, for now, we have estimated optical modal gain by analyzing the stripe-length dependence of edge-emission intensity using the Shaklee's model. It is shown that an optical gain peak appears at ~550 nm although the gain peak value is almost zero, not clearly positive, and that the gain peak shows blue-shift with increasing excitation power. We consider that these results are the evidence of that the red InGaN QW layer has the optical gain. The blue-shift can be explained by the gain saturation due to small density-of-states in InGaN QWs with large alloy compositional fluctuation, and it can also explain the observed gain peak wavelength much shorter than LED emission wavelength (~620 nm). In addition, small values of optical modal gain and short-wavelength peak position can also be explained by the calculated wavelength dependence of OCFs in this layer structure.

OD-Thu-P6* - Micro-Scale Light-Emitting Diodes with Bandwidth up to 7.2 GHz Estimated from Equivalent Circuit Model

3. Optical devices

XINRAN ZHANG[1]
ZHIBIAO HAO[2], CHANGZHENG SUN[2], BING XIONG[2], YANJUN HAN[1], JIAN WANG[2], HONGTAO LI[1], LIN GAN[2], YI LUO[2], LAI WANG[1]
[1] State Key Laboratory of Widegap Semiconductor Optoelectronic Materials and Technologies, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
[2] Beijing National Research Center for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China

Abstract text: As data transmission demands grow rapidly, traditional electrical interconnects face limitations in bandwidth and power efficiency. Optical interconnects offer a promising alternative, and micro-LEDs have emerged as ideal light sources due to their fast response, low power consumption. Currently, the highest reported E-E -3 dB bandwidth for micro-LEDs is 3.6 GHz. However, achieving a 10 Gbps NRZ-OOK data rate requires at least 7 GHz bandwidth.

In this paper, to overcome the RC delay that limits blue micro-LED bandwidth, we fabricated smaller micro-LEDs to reduce RC effects and enhance bandwidth. Eight sizes ranging from 5 μm to 40 μm in diameter were designed, each featuring a top-side DBR structure to enhance optical output power while maintaining a short differential carrier lifetime.

The devices were tested using an Alphalas UPD-50 photodetector with a nominal 7 GHz bandwidth. However, the actual -3 dB bandwidth of the UPD-50 is limited to 3.6 GHz in the blue region after calibration. Within this effective range and under a current density of 1000 A/cm², measured bandwidths for micro-LEDs with diameters of 15 , 20, 25, 30, 35 and 40 μm were 3.58, 3.38, 2.86, 2.59, 2.38, and 2.33 GHz, respectively. For the 5 μm and 10 μm devices, measured bandwidths were 3.84 GHz and 3.71 GHz, respectively. However, due to the limited detector bandwidth, the actual bandwidths of these two smaller devices are likely higher than the measured values.

To estimate the actual bandwidths of the 5 μm and 10 μm devices, we constructed and fitted an equivalent circuit model. The model includes two parallel RC pairs $R_{in}||C_{in}$ and $R_{out}||C_{out}$ representing carrier recombination inside and outside the active region, series resistance R_S, parasitic capacitance C_P, and load resistance R_L. R_{in} and C_{in} determine the recombination-limited bandwidth, while C_P and $R_S||R_L$ mainly determine the RC-limited bandwidth. The model was fitted to 15-40 μm devices to isolate parameter effects on bandwidth. The recombination-limited bandwidth is ~7.37 GHz and remains constant; C_P increases and R_S decreases with diameter. Using the fitted parameters, the RC-limited bandwidths for 15-40 μm devices were calculated and found to match the measured results. Based on these trends, the model was extrapolated to smaller sizes, estimating E-E -3 dB bandwidths of 4.5 GHz for 10 μm and 7.2 GHz for 5 μm micro-LEDs.

OD-Thu-P7 - Enhancing Light Extraction in Nanorod LEDs through Size-Dependent Resonance Effects

3. Optical devices

Ja-Yeon Kim[1]
EunA Hong[1], Min-Ki Kwon[2]
[1] Photonics semiconductor research center, KOPTI, Gwangu, South Korea
[2] Photonic technology, Chosun university, Gwangu, South Korea

Abstract text: We fabricated nanorod LEDs by performing nanoimprint lithography on a 4-inch LED wafer. First, a SiO_2 hard mask was deposited, followed by a Cr layer. A resin layer was then coated, and nanoimprint lithography was used to create nanoscale patterns with a feature size of approximately 500 nm. Using this template, we formed tapered nanorods with an initial diameter of 550 nm. By varying the etching time and temperature in a KOH solution, we successfully controlled the nanorod diameter from 550 nm to 370 nm. Photoluminescence (PL) measurements revealed a significant enhancement in light extraction efficiency as the diameter decreased, with the 370 nm nanorods exhibiting an ~18-fold increase in efficiency compared to the initial structures. This remarkable enhancement is attributed to the increased confinement of light within individual nanorods as their size decreases. Unconfined light propagates laterally, enabling reabsorption by neighboring nanorods, which facilitates photon recycling and amplifies light extraction. This resonant coupling effect was experimentally validated through SEM, PL, CL, and power-dependent PL measurements. Additionally, FDTD simulations were performed to further investigate the underlying physical mechanisms. Our findings provide valuable insights into optimizing nanorod LED structures for enhanced optical performance. **Acknowledgement**

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OD-Thu-P8* - Semi-polar (20-21) InGaN/GaN-based MCLED array with orthogonally polarized emissions

3. Optical devices

Wei Ou[1]
Qingling Jia[2], Jingfeng Duan[2], Leiying Ying[2], Yang Mei[2], **Baoping Zhang**[1]
[1] Institute of Nanoscience and Applications, Southern University of Science and Technology, Shenzhen 518055, China
[2] Laboratory of Micro/Nano-Optoelectronics, School of Electronic Science and Technology, Xiamen University, Xiamen 361005, China

Abstract text: Abstract: Orthogonally polarized lights are highly desired for various applications such as communications, stereoscopic displays, and biomedical imaging modalities. In our previous study [1], we demonstrated that a semipolar GaN-based microcavity light emitting diode (MCLED) could simultaneously emit green light with perpendicular and parallel polarizations to the c∗-axis. Orthogonally polarized emission with a narrow linewidth (∼0.2 nm) arises from the valence band splitting and birefringent nature of the semipolar GaN material, as well as the mode selection of the resonant cavity. In the present work, significant improvements in output power is achieved by employing a silver (Ag) bottom reflector which benefits the thermal dissipation. Arrays are also fabricated and the orthogonally polarized emissions are maintained, with mode groups I and II exhibiting high polarization degree of 0.67 and 0.82, respectively,as shown in figure 1(a). A 3*3 MCLED array in parallel configuration was able to produce high output power of 0.66 mW,as shown in figure 1(b). Through systematic adjusting of material composition ratios, this methodology suggests strong potential for extending the operational wavelength range to encompass blue, red, and violet spectral regions while maintaining orthogonal polarization.

Figure 1 (a) Polar plot of the normalized EL intensity in polar coordinates of a MCLED array. (b)The light output power of MCLED arrays and a single LED device. Insert is a picture of 3*3 MCLED arrays under injection current of 2 mA.

Reference

1 W. Ou *et al. Nanophotonics-Berlin*, vol **13**, pp. 75-83, 2024.

OD-Thu-P9* - Demonstration of GaN-based Resonant Cavity Light-emitting Diodes and Photodetectors by Micro-Transfer Printing

3. Optical devices

Zhi Li[1]
Huanqing Chen[2], Brendan Roycroft[1], Muhammet Genc[1], Xiaodong Hu[2], Brian Corbett[1]
[1] Tyndall National Institute, University College Cork, Cork, T12 R5CP, Ireland
[2] State Key Laboratory for Artificial Microstructure and Microscopic Physics, School of Physics, Peking University, Beijing 100871, China

Abstract text: The resonant-cavity (RC) structures, consisting of two reflective mirrors, provide many advantages for both the light-emitting diodes (LEDs) and the photodetectors (PDs). The LED performance can be improved with the resonant cavity by obtaining emissions with reduced divergence angle and narrower spectral linewidth, thus achieving directional light emission and higher color purity. They also exhibit much more stable wavelengths when varying the injection currents due to the cavity modes. These advantages make the RCLEDs become promising candidates in applications such as virtual reality and augmented reality displays where directional emissions with high color purity and stability are required. On the other hand, the resonant-cavity enhanced photodetectors (RCEPDs), exhibit high responsivity at certain wavelengths due to the narrow spectral linewidth and enhanced absorption, making them very useful for high-resolution imaging and sensing.

For GaN-based RCLEDs and RCEPDs, one of the main obstacles is the fabrication of the top and bottom mirrors. The epitaxial distributed Bragg reflector (DBR) suffers from the build-up strain and dislocations, while the conventional dielectric DBR based on laser liftoff to remove the substrates can induce cracks and rough surfaces. In this work, an approach using the micro-transfer printing technique was demonstrated, where the InGaN/GaN LED epilayers with dielectric DBRs on the top were first released from the sapphire substrate via the photoelectrochemical (PEC) etching and then transfer-printed onto the aluminum (Al) mirrors on the new substrate. The metal connection was finally deposited to allow detailed optical and electrical characterization. The performance under both the light emission and light detection modes were analyzed and discussed. Two distinct cavity mode peaks appear in the spectrum with wavelengths of 447 nm and 469 nm, and spectral linewidths of 4.8 nm and 4.1 nm, respectively. Due to the resonant cavity, the blue shift of the peak wavelength with increasing current densities is significantly reduced from 12 to less than 2 nm. This demonstration paves a new pathway for GaN RC-based structure fabrication, which could benefit many applications such as augmented reality and visible light communications.

OD-Thu-P10* - Low-Temperature Characteristics of Polarization-Doped Nitride Emitters

3. Optical devices

Muhammed AKTAŞ[1]
Anna KAFAR[1], Łucja MARONA[1], Szymon GRZANKA[1], Szymon STANCZYK[1], Przemysław WISNIEWSKI[1], Piotr PERLIN[1]
[1] Institute of High-Pressure Physics PAS, „Unipress", Warsaw, Poland

Abstract text: Nitride semiconductors are crucial for visible to ultraviolet (UV) optoelectronics. Their wide bandgap presents significant doping challenges, particularly for effective p-type conductivity. Magnesium (Mg) is the only successful, relatively efficient p-type dopant, but its high activation energy (160-200 meV in GaN, up to 630 meV in AlN) severely limits free hole concentration. Only about 1% of Mg atoms contribute free holes, and this plummets at cryogenic temperatures, impacting device performance.

These wurtzite semiconductors have the highest spontaneous polarization among III-V semiconductors. A compositional gradient along the growth direction creates a fixed volume polarization charge, attracting free carriers for n/p-type conductivity—polarization doping. Precisely controlling the gradient profile and layer thickness tunes free carrier concentration. Unlike Mg doping, polarization doping provides temperature-independent carrier density, promising for cryogenic applications.

In this study, we present polarization-doped p-cladding layer LED and laser structure. The LED structure successfully works until 20 K with modest voltage change and electroluminescence (EL) intensity that rises with temperature—contrary to Mg-doped counterparts. For laser structure, we managed to reach a relatively low threshold current (40 – 50 mA) with around 1 W/A slope efficiency. Cryogenic measurements revealed distinct behavior above and below 160 K: in continuous wave (CW) mode, the threshold current remained stable up to 160 K but increased thereafter due to Mg acceptor freeze-out. Although, the slope efficiency decreases to 160 K and increases rapidly above the room temperature value. A sudden voltage drop observed at 140 K suggests self-heating-induced conductivity enhancement in the Mg-doped electron-blocking layer (EBL). To mitigate self-heating, pulsed measurements (200 ns pulse width, 0.02% duty cycle) were employed, stabilizing performance up to 160 K. Beyond this temperature, however, lasing ceased entirely, likely due to thermal carrier leakage or defect-activated non-radiative pathways. These results underscore polarization doping's potential for cryogenic applications, where traditional Mg doping falters.

OD-Thu-P11* - Electrochemical lift-off of GaN films for GaN-on-GaN technology

3. Optical devices

Meixin FENG[1]
Qian SUN[1], Hui YANG[1]
[1] Suzhou Institute of Nano Tech and Nano Bionics, Chinese Academy of Science, Suzhou,China

Abstract text: GaN is an important semiconductor with a direct bandgap, and has been widely used for LEDs, lasers, HEMTs and so on. GaN epitaxial layers are usually grown on foreign substrates such as sapphire, Si and SiC. However, these substrates exhibit significant lattice and thermal mismatches with GaN, seriously deteriorating the device performance. Therefore, highly efficient devices with the requirements of high-quality materials are often grown on free-standing GaN substrates.

However, to fabricate various GaN-based devices, GaN substrate removal is often necessary. For instance, GaN-based vertical-cavity surface-emitting lasers with double-sided dielectric distributed Bragg mirrors require substrate removal with accurate controls of the remaining thickness and roughness. GaN-based lasers with an inverted ridge waveguide need substrate removal with the controlled thickness to form the n-side ridge. More importantly, GaN-based nanomembranes without substrate featured with higher bending capability and better heat dissipation, have wide applications in wearable energy harvesting, piezoelectric devices and heterogeneous integration.

Unlike Si and sapphire, GaN substrate cannot be easily separated by wet chemical etching or laser lift-off. Although photoelectrochemical (PEC) etching has been reported to lift off the GaN substrate, it needs uniform high-energy light illumination and specially designed narrow-bandgap sacrificial layer, making the etching process very complex and difficult to popularize. As compared with PEC etching, conductivity-selective EC etching offers several advantages. However, the unevenness of the etch front presents a challenge. On the other hand, the roughness of the lift-off GaN thin film was still too large as compared with the epitaxial layer.

In this work, we achieved uniform EC etching front, and then realized the lift-off of large area GaN film with a roughness of 0.3 nm. Moreover, we realized the fabrication of GaN-based LED membranes with a complete device structure including contact metals separated from the substrate. Photoluminescence and Raman spectra show that the internal stress after the lift-off was effectively lightened with 1.45 GPa. Electrical measurement results show that both the leakage current and series resistance were largely decreased, strong and uniform EL further proved the well-preserved whole structure.

OD-Thu-P12* - Design and Simulation of InGaN/GaN MQW Mode-Locked Lasers

3. Optical devices

Jianwei Fu[1]
bo lu[1], Yangzi Tan[1], Hoi Wai Choi[1]
[1] University of Hong Kong

Abstract text: Mode-locked lasers (MLLs) are crucial for generating extremely short optical pulses, typically in the picosecond or femtosecond range. The advent of semiconductor-based lasers, such as InGaN/GaN MQW mode-locked lasers, has expanded their application potential by offering advantages like compact size, higher efficiency, and the ability to operate at room temperature. As the trend toward miniaturization and integration of photonic devices on-chip continues, mode-locked lasers, especially those based on InGaN/GaN MQW structures, hold significant promise as low-power, compact, and efficient light sources for integrated photonics. These lasers can be seamlessly integrated with other photonic components such as modulators, detectors, and waveguides, forming the backbone of integrated photonic circuits. Their small footprint and compatibility with semiconductor fabrication processes position them as ideal candidates for future advancements in optoelectronics, quantum photonics, and high-speed data processing on chips. This work focuses on the design and simulation of InGaN/GaN multiple quantum well (MQW) mode-locked lasers, utilizing advanced simulation tools to gain a comprehensive understanding of their performance characteristics. The design process begins with modeling the optical mode profile using Lumerical software to calculate the effective refractive index and group refractive index for the fundamental mode. In the next phase, the MQW gain solver is employed to conduct 4x4 k•p calculations on the electronic band structure of the MQW active region. Absorption properties are then assessed through a coupled CHARGE/MQW simulation. The final simulation step involves performing a one-dimensional traveling-wave laser simulation using INTERCONNECT software. These steps enable accurate modeling of the MQW gain parameters and the time-domain response of the laser, ultimately generating and analyzing the steady-state time-domain waveform of the emitted laser to assess the performance of the mode-locked system. The results demonstrate the feasibility of monolithic GaN-based MLLs for applications in ultrafast spectroscopy and on-chip integrated photonics, highlighting their potential for transformative advancements in both research and technology.

OD-Thu-P13* - Marked Enhancement of Optical Gain by Doping for 10 THz-band GaN-based Quantum-Cascade Laser Analyzed by NEGF method

3. Optical devices

Airu Takahashi[1]
Koki Yabe[1], Akira Kaneko[1], Li Wang[1], Ke Wang[1], Sachie Fujikawa[2], Krishan Kumar[1], Shashank Mishra[1], Thomas Grange[3], Stefan Birner[3], Hiroyuki Yaguchi[2], Hideki Hirayama[1]
[1] RIKEN
[2] Saitama University
[3] nextnano GmbH

Abstract text: Terahertz quantum-cascade lasers (THz-QCLs) have attracted attention as practical THz light sources due to their compact size, high output power, narrow linewidth, long lifetime, and high durability, and are expected to be used in a variety of applications. However, it is difficult to realize over 300K operation by GaAs-based QCL, and their operating frequency range is limited to 1.2-5.4 THz. This is because the electron-LO phonon energy (E_{LO}) of GaAs is 36 meV, which is close to the thermal energy at room temperature. In contrast, GaN-based semiconductors have a large E_{LO} of 92 meV, GaN-based QCL is predicted to operate in the 1.5-15.5 THz range, and it is suitable for over 300K operation. In this study, we demonstrated that the optical gain of GaN-based QCLs can be significantly increased by relatively highly doping, and that the optical gain can be further improved by correcting the design to take into account the mis alignment by the band-bending.

We assume a GaN/$Al_{0.13}Ga_{0.87}N$ 3-quantum well (QW), 4-level structure, and analyzed the optical gain using the non-equilibrium Green's function (NEGF) method to obtain a strict solution. The analysis is including electron-electron scattering, electron-LO phonon scattering, impurity scattering, and interface roughness scattering, and included the effects of quantum level broadening due to fast scattering processes.

We found that increasing the doping concentration in the injection well causes band bending, which generates an energy gap between the lower lasing level and the extraction level, resulting in reducing the optical gain. We also found that by correcting the injection layer thickness even higher optical gain can be obtained under higher doping concentration.

Applying these optimizations to a GaN/AlGaN 10 THz-QCL, it was found that the optical gain during doping increased significantly and the maximum optical gains obtained were 140, 95, 30 cm-1 at 10 K, 200 K, and 350 K, respectively. In particular, an optical gain of 30 cm-1 was obtained at 350 K operation, indicating that high output power can be expected even at high temperatures by controlling the doping. Furthermore, a similar method was applied to an InGaN/GaN 10 THz QCL, and it was confirmed that a significant improvement in optical gain could be also obtained.

OD-Thu-P14* - Design and Fabrication of GaN/AlGaN THz Quantum-Cascade Laser Structure on SiC Substrate

3. Optical devices

Akira Kaneko[1]
Airu Takahashi[1], Koki Yabe[1], Li Wang[1], Ke Wang[1], Sachie Fujikawa[2], Krishan Kumar[1], Shashank Mishra[1], Hiroyuki Yaguchi[2], Hideki Hirayama[1]
[1] Riken, Saitama, 351-0198 Japan
[2] Saitama University, Saitama, 338-8570 Japan

Abstract text: GaN-based semiconductors have a large LO-phonon energy of 92 meV, so the use of inter sub-band transition (ISBT) is expected to enable room-temperature operations of far-infrared semiconductor lasers, which has not been achieved until now. We have predicted room-temperature lasing in a wide frequency range of 2 to 15 THz from the optical gain analysis of GaN-based terahertz quantum-cascade lasers (THz-QCLs). It has been found that the sapphire substrate, which is often used for GaN semiconductor epitaxial growth, cannot be used as a substrate of GaN THz-QCL waveguides, because its refractive index in the terahertz region is larger than that of GaN. Therefore, in this study, we designed a GaN-based single-metal plasmon waveguide on a SiC substrate with a low refractive index, and fabricated a GaN/AlGaN QCL structure on the SiC substrate by MOCVD.

The single-metal plasmon waveguide was designed using waveguide analyzing software. The complex refractive index of the metal and doped semiconductor layers was calculated using the Drude-model. We analyzed the metal plasmon waveguide of 3-10 THz GaN-based QCL and showed that it is possible to design a waveguide that simultaneously satisfies an optical confinement factor of 60% or more and a low loss of 30 cm-1 or less.

A 2 μm thick Al0.13Ga0.87N buffer layer was grown both on AlN/c-sapphire and on AlN/SiC, and 50 periods of GaN/Al0.13Ga0.87N-QCL structures were grown on top of it. The threading dislocation density (TDD) of the AlN layer was approximately 1×1019 cm-2 for both. Reasonable X-ray satellite peaks were observed from the grown QCL structures. The X-ray satellite peaks demonstrated that the QCL grown on sapphire/AlN had a layer thickness that was very accurately formed with an error of within 1%. The QCL structure fabricated on a SiC substrate also demonstrated a clear periodic structure that was confirmed by cross-sectional TEM image. However, the layer thickness error was more than 20%. This is thought to be because the substrate surface temperatures during MOCVD growth were different between SiC and sapphire, causing changes in the growth rate. In the future, we plan to achieve accurate layer thickness by controlling the growth temperature during growth on a SiC substrate, and to achieve lasing of GaN QCLs by completing a waveguide fabrication process.

OD-Thu-P15* - Design, Growth, and Characterization of Al(x)In(y)Ga(1−x−y)N-Based Integrated Infrared-Visible Detector-Emitter

3. Optical devices

Alireza Lanjani[1]
Benjamin McEwen[1], Prachi Garg[2], Vincent Meyers[3], Shaon Das[2], Emma Rocco[4], David Hill[5], Winston K. Chan[5], Baishakhi Mazumder[2], F. Shadi Shahedipour-Sandvik[1]
[1] Department of Nanoscale Science and Engineering, State University of New York-Albany, Albany, NY, USA
[2] Department of Materials Design and Innovation, University at Buffalo, Buffalo, NY, USA
[3] Sandia National Laboratories, Albuquerque, NM, USA
[4] U.S. Naval Research Laboratory, Washington, D.C., USA
[5] SRI International, Princeton, NJ, USA

Abstract text: Due to the wide and tunable bandgap energy of III-Nitrides, most research conducted over the past few decades has focused on applications requiring this large bandgap, such as blue and ultraviolet (UV) light-emitting diodes. Because of this large bandgap, the infrared (IR) applications remained mostly untouched. Since introducing the idea of using multi-quantum wells (MQWs) for IR detection[1], these detectors have attracted attention for IR detection. In this approach, by surrounding a wide bandgap material (GaN) with a larger bandgap material ($Al_xGa_{1-x}N$), an "artificially" small bandgap region is created to form a quantum well IR detector (QWIP). Instead of interband transitions, transitions are inter-subbands of the conduction or valence bands.

To capture and read the photocurrent in QWIPs, an additional readout circuit is essential, necessitating pixelated design and increasing device complexity, which is unfavorable in large focal plane array applications. To overcome this challenge, an integrated GaAs-based detector-emitter design was demonstrated in the 1990s, where absorption of mid or far IR in the QWIP, creates photoexcited carriers that cause excitation in the emitter to generate IR light[2]. This upconverted light is then detected by a camera to form an image. The generation of visible light will further reduce system complexity.

In this work, we demonstrate the device design, metal organic chemical vapor deposition (MOCVD) growth, device fabrication, and material and electrical characterizations of a *p*-type (Mg-doped) $Al_xGa_{1-x}N$/GaN QWIP for IR detection integrated with an $In_xGa_{1-x}N$/GaN MQW emitter for emission in the visible range. Photodetectors were fabricated to measure dark current density and photocurrent. Our results showed very low photoresponsivity (<5 μA/W), due to multiple factors[3], such as insufficient carrier population in the wells. To further enhance responsivity, atom probe tomography (APT) was utilized to interrogate [Mg] and distribution.

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OD-Thu-P16 - Optimizing AlGaN Barrier Thickness for Enhanced Responsivity in GaN-on-Si HEMT UV Detectors

3. Optical devices

Abdalla Eblabla[1]
Arthur Collier[1], Aasif Bahat[1], Elham Yadollahifarsi[1], Menno J. Kappers[2], David J. Wallis[1], Rachel A. Oliver[2], Khaled Elgaid[1]
[1] Cardiff University, Cardiff, United Kingdom
[2] University of Cambridge, Cambridge, United Kingdom

Abstract text: AlGaN/GaN high-electron-mobility transistors (HEMTs) on Si are promising for UV detection due to their cost-effectiveness and high internal gain, making them key for future robotics, civil, and space-based optoelectronic applications. Recent efforts to enhance photoresponsivity have explored nanohole etching of the barrier surface [1]. Additionally, AlGaN barrier properties (thickness and Al composition) and gate bias significantly impact HEMT performance. This paper studies the influence of the AlGaN barrier on the electrical and optical performance of AlGaN/GaN HEMT UV detectors on a GaN-on-Si substrate for optimum photoresponsivity.

AlGaN/GaN HEMTs were fabricated on a 6-inch Si substrate [2]. Wafers with varying AlGaN barrier thicknesses (14, 19, and 26 nm) were processed simultaneously, where the Al composition was adjusted to maintain a relatively constant channel density. DC-IV measurements were conducted to evaluate device performance. Initial characterization under dark conditions revealed that as the AlGaN barrier decreased, the pinch-off voltage (V_P) increased along with peak transconductance (G_M). Under UV illumination in the off-state region, where the gate-source voltage (V_{GS}) < V_P, all devices exhibited a drain-to-source current (I_{DS}) increase as the wavelength (λ) decreased. The photocurrent (ΔI_{DS}) performance was measured at λ = 395 and 365 nm, where all the light was absorbed in the GaN layers. Thus, all the photosensitivity was due to the leakage in the GaN layers below the channel. To ensure an accurate comparison among structures, ΔI_{DS} was measured at $V_{GS} = V_P + 3$ V. The dependence of photoresponsivity on V_{GS} bias was also studied. Devices with 14 nm and 26 nm AlGaN exhibited lower photoresponsivity compared to the 19 nm AlGaN, where a peak UV responsivity of 1.3×10^7 A/W was achieved. Furthermore, UV responsivity degraded notably as λ increased due to the reduction in light absorption in the GaN layers. These findings highlight the importance of balancing channel conductivity and surface distance, as excessive thinning of the AlGaN barrier can lead to increased current leakage and trapping effects.

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OD-Thu-P17* - The quatification of the interband transitions in the quantum confined Stark Effect

3. Optical devices

Sha Han[1]
Ke Xu[1]
[1] The Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, Suzhou, China

Abstract text: The potential applications in optical devices such as μ-LED, high-speed modulators, wavelength selective detectors and optically bistable switches have motivated strong interest in the quantum confined Stark Effect (QCSE) in the heterostructures. However, the quantification of the QCSE is difficult and complicated which is currently limited to the allowed interband transitions. For the forbidden transitions, the solving process is time-consuming and the crossings of the forbidden transitions may appear when the electric field increases. Thus, a more accurate description of the light emission or absorption properties of quantum wells under the applied electric field is urgently needed. Here, we propose a 3D-plot to study the interband transitions. By the Wentzel–Kramers–Brillouin approximations, we deduce that the average interband transition spacing ΔE below or near the E_g is innert to the electric field strength and the ΔE is inversly proportional to the square of the quantum well's width L by 4πh_bar^2/sqrt($m_e m_h$) below the E_g and 12πh_bar^2/sqrt($m_e m_h$) slightly above the E_g. The simulations further validate the 2 scaling laws and the influence of the charge's screening is also studied.

OD-Thu-P18* - A Quick Blood Test for Lung Cancer by Nitride Surface-Enhanced Raman Spectroscopy

3. Optical devices

Thuy Doan Khanh Huynh[1]
Huy Kim Nhat[1], Fang-Ching Chien[1], Kun-Yu Lai[1]
[1] National Central University

Abstract text: Early and accurate lung cancer diagnosis remains a critical challenge, particularly in non-invasive blood-based screening. Traditional liquid biopsy methods, while promising, suffer from low biomarker effectiveness and prolonged processing time, highlighting the need for advancements in blood test for cancer. In this study, we address this limitation by integrating InGaN quantum wells, surface-enhanced Raman scattering (SERS), and machine learning to test human blood plasma for lung cancer and other cancers in the breast, endometrium, pancreas, and colon. By capturing the SERS signals of carotenoids, enhanced by the InGaN quantum wells, our biochip can identify the blood with lung cancer in 25 minutes with the accuray above 90 %. These results open a new opportunity for blood-based cancer diagnostics with high speed and high accuracy.

OD-Thu-P19 - Theory of contact to p-type GaN – new multilayer design

3. Optical devices

Konrad S[1]
Pawel Strak[1], **Stanislaw Krukowski**[1]
[1] Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142 Warsaw, Poland

Abstract text: Electrical properties of contact to p-type nitride semiconductor devices, based on GaN and AlN are dominated by Fermi level difference related to huge difference of work functions of all metals and p-type of gallium, aluminum and indium nitrides and their solid solutions. The results is nonohmic character of the contact which is demonstrated in high current part of I-V diagrams of the diodes both laser diodes (LDs) and light emitting diodes (LEDs). The electrical nature of the Ni-Au contact formed by annealing in oxygen atmosphere is elucidated [1]. A new type of the contact, based on these investigations is designed. The contact is based on application of multiple layer implantation processes. The implementation of such design promise to provide superior characteristics (resistance) as compared to other contacts used in bipolar nitride semiconductor devices. The development of such contact will remove one of the main obstacles in development of highly integrated nitride optoelectronic devices: energy loss and the excessive heat production close to the multiple quantum wells system.

ED-Thu-P1* - Engineering of Interface Barrier in MXene/GaN for Schottky Diode Applications and Contact Performance

4. Electronic devices

Dominika Majchrzak[1]
Karol Kulinowski[2], Wojciech Olszewski[1], Rafał Kuna[1], Daria Hlushchenko[1], Adrianna Piejko[1], Miłosz Grodzicki[1], Detlef Hommel[1], Robert Kudrawiec[1]
[1] Łukasiewicz Research Network – PORT Polish Center for Technology Development, Wrocław, Poland
[2] Department of Semiconductor Materials Engineering, Wrocław University of Science and Technology, Wrocław, Poland

Abstract text: MXenes possess unique properties such as metallic conductivity, mechanical flexibility, high transmittance, and chemical stability, making them ideal for electrode applications in optoelectronic and electronic devices [1–4]. Their wide work function range (1.6–6.2 eV [4,5]) enables versatile contact engineering. The Fermi level position at heterostructure interfaces, critical for device performance, can be influenced by surface phenomena. Given the widespread use of wurtzite GaN-based devices and the potential of MXenes to improve electrical contacts, understanding the MXene/GaN interface is essential.

This study employed contactless electroreflectance (CER) to analyze the built-in electric field in MXene/GaN structures and used X-ray and UV photoelectron spectroscopies (XPS and UPS) to investigate physicochemical properties [6]. Five different MXene, exhibiting high work function (Cr_2C, Mo_2C, V_2C, V_4C_3, Ti_3C_2), were examined. It was shown that covering GaN with all studied MXenes shifted the surface Fermi level, increasing the interface barrier. Post-annealing of the samples at 750 °C further elevated the barrier heights and ionization energies\work functions. Moreover, it has been shown that removing excess MXene material did not affect the built-in electric field, highlighting the robust physicochemical stability of MXenes on GaN. To demonstrate the potential of engineering the MXene/GaN interface, Schottky diodes were fabricated using Mo_2C and V_2C, which exhibited the highest barrier heights. The I–V measurement revealed that transferring MXene onto the GaN surface increases the forward voltage and reduces the reverse current, indicating an increased potential barrier. This study also identified the types of MXene materials capable of forming Schottky contacts and ohmic contacts with the surface of GaN-based semiconductors.

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ED-Thu-P2* - Fabrication of GaN Junction Barrier Schottky Diodes using p-GaN Selective-Area Growth

4. Electronic devices

Qi Shu[1]
Alexander Brand[1], Arno Kirchbrücher[1], Arne Debald[2], Michael Heuken[3], Holger Kalisch[1], Andrei Vescan[1]
[1] Compound Semiconductor Technology, RWTH Aachen, Aachen, Germany
[2] Application Laboratory, AIXTRON SE, Herzogenrath, Germany
[3] Corporate Research & Development, AIXTRON SE, Herzogenrath, Germany

Abstract text: The GaN junction barrier Schottky diode (JBS) has attracted much attention in recent years. However, forming the required lateral p-n junction remains challenging. Selective-area p-type doping via Mg ion implantation requires ultra-high pressure and temperature for dopant activation [1,2], introducing point defects. This work presents an alternative approach: etching grooves into an n^--GaN layer and selectively regrowing p-GaN using MOCVD with an Al_2O_3/SiO_2 hard mask. This 2-layer mask suppresses SiO_2 thermal decomposition, limits the resulted n-type parasitic doping concentration to $3–9\times10^{15}$ cm^{-3}, and enables lift-off with BOE.

The regrowth template comprises 1.8 µm n^+-GaN (3×10^{18} cm^{-3}) and 1 µm n^--GaN (5×10^{15} cm^{-3}) grown via MOCVD on a 2-inch sapphire wafer. A 200 nm SiO_2 layer was deposited via PECVD, followed by 25 nm Al_2O_3 via ALD. A single lithography step allows successive etching through the hard mask and into n^--GaN, creating 500 nm deep parallel trenches (5 µm width/spacing). After photoresist removal, p-GaN was selectively regrown to fill the trenches and then activated. Hall measurements of a reference structure confirmed a hole concentration of 4×10^{17} cm^{-3}. After hard-mask lift-off in BOE, a deep etch of a circular mesa exposed the n^+-GaN, followed by the cathode (Ti/Al/Ni/Au) deposition on n^+-GaN and the anode (Ni/Au) formation on the mesa.

I-V measurements revealed a leakage current density of ~10^{-4} A/cm² at -8 V, likely due to remaining dry-etching damage. The rectification ratio between -8 V and 2 V was ~10^6. The turn-on voltage was ~1.25 V, higher than a standard Schottky diode (~0.7 V) but lower than a p-n diode (~3.2 V). The extracted ideality factor was 1.19, and the differential specific on-resistance was 3.1 mΩ·cm², comparable to recent JBS reports. The breakdown voltage was ~60 V, corresponding to a critical field of ~1.04 MV/cm, likely limited by breakdown along the mesa edge. Future work will focus on improving electrical performance through better etch damage mitigation and device passivation.

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ED-Thu-P3* - Tunneling current in Schottky structures formed on heavily doped n-type GaN

4. Electronic devices

Masahiro Hara[1]
Mikito Nozaki[1], Takuma Kobayashi[1], Heiji Watanabe[1]
[1] The University of Osaka, Suita, Osaka 565-0871, Japan

Abstract text: Modeling the carrier transport properties at electrodes formed on heavily doped GaN without an alloying process (i.e., heavily doped GaN Schottky contacts) is an important first step toward improving the ohmic contact formation process. In this study, a vertical Schottky barrier diode (SBD) structure was fabricated using n-type GaN epitaxial layers with a net donor density of 1.5×10^{18} cm^{-3}, which is comparable to the effective density of states in the conduction band ($\sim2\times10^{18}$ cm^{-3}). The current-voltage (*I-V*) characteristics of the non-sintered contacts were analyzed by performing a numerical calculation of the tunneling current, including both thermionic field emission (TFE) and field emission (FE).
The ideality factor in the forward *I-V* curve was 1.2, deviating from unity, and a large current (> mA/cm^2) was observed under a small reverse bias (< 10 V). These results indicate that carrier transport is not described by the conventional thermionic emission (TE) but by tunneling current. Thus, we analyzed the forward and reverse *I-V* characteristics based on the fundamental formula for tunneling current. As a result, the experimental *I-V* curves were well reproduced by the calculation assuming the Schottky barrier height of 1.13–1.16 eV, which is consistent with that obtained by capacitance-voltage measurement (1.21 eV).
While the numerical formula does not assume only one type of tunneling model (TFE or FE), we can distinguish which transport is dominant by investigating the energy where electron tunneling most frequently occurs, defined as E_{peak}. Under a forward bias, E_{peak} is located at the energy higher than the conduction band edge (E_C), and TFE transport is dominant in the entire voltage range measured. On the other hand, E_{peak} sharply decreases toward the Fermi level in the metal (E_{Fm}) in the reverse characteristics, indicating that the dominant conduction mechanism changes from TFE to FE due to a high electric field at the Schottky interface.

This work was supported by the MEXT "Program for Creation of Innovative Core Technology for Power Electronics" (JPJ009777) and JSPS KAKENHI (23K13367 & 24KJ0142).

ED-Thu-P4* - Experimental Analysis and Performance Evaluation of GaN PiN Betavoltaic Cells

4. Electronic devices

Jaewon Park[1]
Hyeon-Tak Kwak[2], Hyun-Woo Lee[2], Donghan Kim[2], Hoe-Min Kwak[2], Dong-Young Kim[2], Dong-Seok Kim[3], Jeong-Gil Kim[4], Hongsik Park[5], Sung-Bum Bae[2], Hyung-Seok Lee[2]
[1] Electronics and Telecommunications Research Institute (ETRI), Daejeon, South Korea / School of Electronic and Electrical Engineering, Kyungpook National University, Daegu, South Korea
[2] Electronics and Telecommunications Research Institute (ETRI), Daejeon, South Korea
[3] Korea Multi-Purpose Accelerator Complex, Korea Atomic Energy Research Institute (KAERI), Gyeongju, South Korea
[4] Department of Semiconductors, Dong-A University, Busan, South Korea
[5] School of Electronic and Electrical Engineering, Kyungpook National University, Daegu, South Korea

Abstract text: Betavoltaic (BV) cells, which use radioactive isotopes, are a promising next-generation energy source that provides long-term stable power independent of environmental conditions or external energy sources. GaN, a wide bandgap semiconductor, is a promising material for BV cells because GaN-based BV cells can enable higher theoretical output voltage and power conversion efficiency, along with strong radiation hardness ensuring stable operation.

In this study, we focused on the fabrication process of GaN PiN BV cells and the evaluation of their electrical properties and power performance. The BV cells were characterized under 17 keV e-beam irradiation, which corresponds to the average energy of the Ni-63 radioisotope, using a probe workstation equipped with a scanning electron microscope (SEM). Key parameters, including short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}), were extracted from the measured I-V characteristics to evaluate the power performance of the BV cells. Additionally, we analyzed device characteristics under varying e-beam accelerating voltages within the energy spectrum range of Ni-63 beta decay.

BV cells have potential as long-term stable power sources for applications such as space exploration, implantable medical devices, and remote sensor systems. Therefore, BV cells are expected to emerge as a reliable and efficient alternative to conventional batteries.

ED-Thu-P5* - Deep-Level Defects Induced Degradation of Negative Differential Resistance in GaN-Based Resonant Tunneling Diodes

4. Electronic devices

Haibing Qiu[1]
Ting Liang[1], Lifeng Bian[2]
[1] State Key Laboratory of Widegap Semiconductor Optoelectronic Materials and Technologies, North University of China, Taiyuan, China
[2] Frontier Institute of Chip and System, Fudan University, Shanghai 200433, China

Abstract text: The degradation of the negative differential resistance (NDR) of GaN-based resonant tunneling diodes (RTDs) is a primary factor that limits their development into terahertz light source devices. In this work, on the basis of experiments and first-principles calculations, we proposed that deep-level defects in epitaxial materials can significantly affect the NDR of GaN-based RTDs. According to a low-frequency noise test, we confirmed the existence of 0.2l and 0.54 eV deep level defects at the active region tunneling interface. The first-principles study of defect calculation based on the mixed functional theory reveals that the two deep-level defects originate from the interstitial defect N_i, and the defect pair V_N-N_{Ga} of the GaN side in the tunneling interface, respectively. In addition, AFM and TEM results indicate that threading dislocations are not the main factor fueling NDR degradation in the prepared RTDs. Our work suggests that the elimination of deep-level defects is the key to obtaining steady and reliable NDR in GaN-based RTDs.

ED-Thu-P6* - Avalanche Signature Analysis in state of the art GaN-on-Si Vertical PiN Diodes

4. Electronic devices

Youssef HAMDAOUI[1]
Adrien Bidaud[1], Sondre Michler[2], Katir Ziouche[1], Farid Medjdoub[1]
[1] CNRS-IEMN, Lille, France
[2] Department Innovation Management Siltronic AG, München, Germany

Abstract text: In this work, state-of-the-art 800 V and 1200 V class vertical GaN-on-Si PiN diodes were fabricated, employing drift region thicknesses of 4.5 µm and 7.4 µm with a net Si doping concentration of 9×10^{15} cm^{-3}. The device structure features a 700 nm p-type region with an active Mg doping concentration of 3×10^{17} cm^{-3}. and a 500 nm n-type region with a net Si doping concentration of 3×10^{18} cm^{-3}. The epitaxial growth, performed by Siltronic**,** employed an optimized buffer layer.

In the off-state, the diodes demonstrate uniform breakdown across sizes ranging from 50 µm to 1000 µm in diameter. The breakdown voltage exceeds 800 V for the 4.5 µm PiN diode and 1200 V for the 7.4 µm PiN diode. Both diodes exhibit a soft breakdown that intensifies with temperature (RT to 70°C), indicative of an avalanche signature. To analyze this behavior, the temperature dependence coefficient (α) of breakdown voltage was extracted, using the equation : $BV(T) = BV(25°C)(1 + \alpha((\Delta T))$. For small diodes (d = 100 µm), α is 2.4×10^{-4} K^{-1} for the 4.5 µm PiN diode and 1×10^{-4} K^{-1} for the 7.4 µm PiN diode. This suggests a potentially higher defect density in the latter, likely due to stress from thick growth and / or process-induced damage from deeper mesa etching (55% longer than for the 4.5 µm PiN diode). As the diode size increases, α decreases, reaching 1×10^{-4} K^{-1} for the 4.5 µm diode and -4.85×10^{-4} K^{-1} for the 7.4 µm diode. This trend is attributed to defect-assisted tunneling or trap-assisted recombination, which play a more significant role in larger diodes, potentially preventing the avalanche current generated by impact ionization. The leakage current is linked to dislocation density, growth-related defects in GaN on silicon and sidewall defects. Comparison with reported 1200 V GaN-on-GaN diodes reveal that GaN-on-Si diodes exhibit significantly higher leakage, increasing from 34 µA/cm² to 220 µA/cm² at 800 V and reaching 2 mA/cm² at 1000 V In GaN bulk diodes, leakage current increases from 2 µA/cm² at 600 V to 7 µA/cm² at 1000 V, compared to GaN-on-GaN PiN diodes ranges from 3.5 to 4.6×10^{-4} K^{-1}.

In the on-state, the diodes achieve a low specific on-resistance (Ron) of 0.4–1.7 mΩ·cm², depending on diode size, and deliver high currents up to ~12 A. This results in an outstanding Baliga figure of merit (BFOM) of 3 GW/cm², favorably comparable to any GaN PiN diode on foreign substrates.

ED-Thu-P7* - Polarization Superjunctions for Reduced Leakage and Enhanced Breakdown Characteristics in GaN-based Field-Effect Schottky Barrier Diodes

4. Electronic devices

Arno Kirchbrücher[1]
Arash Mohammadi[1], Qi Shu[1], Liubou Padzialioshkina[1], Holger Kalisch[1], Andrei Vescan[1]
[1] Compound semiconductor Technology, RWTH Aachen University, Aachen, Germany

Abstract text: Conventional field-effect Schottky barrier diodes (FESBD) fabricated on AlGaN/GaN heterojunctions provide improved breakdown voltages and low reverse-bias leakage currents. However, even if field plates are employed, the electric field peaks at the Schottky contact edge with a sharp decline away from the electrode, limiting reverse operation voltage. In a circular PSJ (polarization superjunction) diode, a ring-shaped region with coupled 2D hole and 2D electron gases (2DHG / 2DEG) is inserted around the central Schottky electrode. The 2DHG of this PSJ region which consists of a GaN/AlGaN/GaN double heterostructure is ohmically contacted and connected to the Schottky metallization. The PSJ can be efficiently depleted under reverse bias. Unlike a space charge region spanning over a depleted 2DEG (with remaining positive polarization charges), the depleted PSJ is overall electrically neutral. As a result, the electrical field distribution is flattened, reducing its peak value and enabling significantly larger voltages before breakdown[1,2]. In our study, we fabricated PSJ diodes and conventional FESBD with different epitaxial layer stack designs and lateral geometries. Measured and simulated capacitance-voltage characteristics show a steep single-step depletion, indicating the PSJ is depleted at lower reverse bias than the 2DEG under the Schottky contact. The current-voltage characteristics demonstrate a strong increase of the breakdown voltage from ca. 600 V (FESBD) to more than 3000 V (PSJ diode). Reverse leakage currents are reduced by up to 4 orders of magnitude, yielding a rectification ratio of more than 10^9. Initial studies of the dependencies of device characteristics on design parameters appear in part to be contrary to expectations. A detailed analysis of device behavior is conducted presently and will be shown. In the future, PSJ devices will also enable a better understanding of the interactions of coupled 2DEG/2DHG e.g. in multi-channel transistors or superlattice buffers.

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ED-Thu-P8* - Reverse current suppression of p-GaN diode using SiOx interlayer

4. Electronic devices

Zixian Jiang[1]
Zhiyuan Liu[1], Tingang Liu[1], Haicheng Cao[1], Zuojian Pan[1], Na Xia[1], Mritunjay Kumar[1], Chuanju Wang[1], Kexin Ren[1], Xiaohang Li[1]
[1] Advanced Semiconductor Laboratory, Electrical and Computer Engineering Program, CEMSE Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Kingdom of Saudi Arabia

Abstract text: The emergence of GaN-based CMOS circuits has garnered growing interest. While significant progress has been made in n-type GaN FETs, developing p-type counterparts, including p-GaN diodes, remains challenging. P-GaN diodes typically exhibit large reverse currents due to the poor Schottky contact between p-GaN and metal, which limits their integration into GaN CMOS applications such as Schottky-gated pFETs and circuit protection. Previous studies[1] have attempted to address this issue with low Mg concentration, which sacrifices on-resistance and current density—the critical factors in developing p-GaN FETs. In this work, we propose a novel p-GaN diode structure incorporating a Si-rich amorphous SiO_x interlayer, which effectively suppresses the reverse current from 2.74×10^{-4} A/μm to 1.57×10^{-6}A/μm at 10V, while maintaining high forward current, from 6.08×10^{-4} A/μm to 5.56×10^{-4} A/μm at -10V. This study highlights the potential of the proposed approach to enhance p-GaN diode performance.

Sample A serves as the reference Schottky p-GaN diode, For samples B and C, a Si-rich amorphous SiO_x layer was deposited via PECVD. In sample B, an additional etching step selectively thinned the SiO_x layer in the Schottky region before the deposition of Schottky metal. Compared to Sample A, Sample B achieves a three-order reduction in the reverse current while maintaining nearly identical forward conduction. Sample C, shows lower forward current, due to the thicker SiO_x layer. The forward conduction follows schottky emission, indicated by the linear $\ln(I)–V^{1/2}$ relationship, while the reverse leakage exhibits a log(I)–1/T dependence, suggesting Poole–Frenkel emission as the dominant mechanism.

XPS data on the Si 2p shows a higher Si^{+3} percentage in SiO_x compared to SiO_2, confirming its Si-rich properties. Within the amorphous SiO_x, the presence of oxygen vacancies causes hopping conduction. The band diagram of the proposed structure shows that oxygen vacancies related to defect level lead to a larger barrier to metal than to the p-GaN. As a consequence, the reverse conduction has been suppressed, while in forward bias, hole injection from the p-GaN remains the same as Sample A.

Reference

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ED-Thu-P9 - Schottky contacts on GaN epilayers grown on bulk substrates

4. Electronic devices

Fabrizio Roccaforte[1]
Giuseppe Greco[1], Patrick Fiorenza[1], Salvatore Di Franco[1], Emanuela Schilirò[1], Raffaella Lo Nigro[1], Filippo Giannazzo[1], Taoufik Slimani Tlemcani[2], Pedro Rocha[2], Eric Frayssinet[3], Florian Bartoli[3], Michal Bockowski[4], Daniel Alquier[2], Yvon Cordier[3]
[1] CNR-IMM - Catania (Italy)
[2] GREMAN UMR 7347, Université de Tours, CNRS-INSA - Tours (France)
[3] Universitè Cote d'Azur, CNRS-CRHEA - Valbonne (France)
[4] IHPP - Warsaw (Poland)

Abstract text: While Gallium Nitride has a great potential for power electronics, today its applications are mainly limited to lateral devices on foreign substrates. In fact, the affirmation of a vertical GaN technology passes through the availability of large-area bulk GaN substrates, although the quality of the available material is often still questionable. In this work, we combine nanoscale analysis on bare material with macroscopic electrical analyses on simple Schottky diodes to assess the properties of the homoepitaxial GaN epilayers grown by MOVPE on different available bulk GaN substrates.

The GaN epilayers have been firstly inspected by nanoscale topographic (AFM) and electrical (Conductive-AFM) analyses. All analyzed samples showed a very smooth surface (RMS ~1 nm on a 50×50 μm^2 area), while the uniformity in the local conductivity strongly depended on the substrate used for the growth.

The properties of the epilayers have been also investigated using Ni/GaN Schottky diodes as test vehicles, acquiring their forward and reverse characteristics before and after an annealing step at 400°C. An improvement of I-V electrical characteristics of the annealed diodes was demonstrated in both forward and reverse bias. Applying the Thermionic Emission (TE) model, we demonstrated a reduction of the ideality factor (n) and an increase of the barrier height (Φ_B) upon annealing.
The forward characteristics at different measurement temperatures confirmed the TE behavior, with a temperature dependence of n and Φ_B that hints towards the formation of an inhomogeneous Schottky barrier. From a Φ_B vs n plot, it was possible to estimate an ideal barrier Φ_{B0} =1.12eV at n=1 in the case of epilayers on ammonothermal substrates. On the other hand, the temperature dependence of the reverse characteristics was better described by Thermionic Field Emission (TFE) model.

A comparative analysis among different substrates revealed the superior behaviour enabled by the ammonothermal bulk GaN. The adopted methodology revealed itself as a simple but efficient way to qualify the properties of the GaN-on-GaN materials for the future development of this technology.

This work has been funded by the ECSEL-JU under Project GaN4AP (Grant Agreement 101007310).

ED-Thu-P10* - Low Leakage Etched-And-Regrown GaN p-n diodes with Fluorine Plasma Treatment

4. Electronic devices

Xingyu Fu[1]
Xuelin Yang[1], Zhenghao Chen[1], Bo Shen[1]
[1] The School of Physics, Peking University, Beijing 100871, China

Abstract text: GaN has gained much attention in power electronics for its superior physical properties such as wide bandgap, high critical electric field. However, the development of vertical GaN power devices has been significantly hampered by the lack of selective-area p-type doping techniques. The acceptor activation rate of Mg-implanted GaN is still low. Considering the successful activation of epitaxially grown p-type GaN, “etching-and-regrowth “emerges as a more desirable and effective route for realizing selective-area doping in GaN.

It’s inevitable to use ICP etching to form selectively regrown areas or trenches before regrowth. However, etching induced damage and exposure to air will introduce high concentrations of Si impurities and trap states at the regrowth interface, leading to excessive leakage current or premature breakdown in regrown p-n junction. Therefore, reducing interfacial Si concentration or compensating Si impurities is critical for achieving low-leakage regrown GaN p-n junctions and p-type selective-area doping.

In this work, a new solution to reduce leakage current of regrown GaN p-n junctions is proposed. By treating the regrowth surface with fluorine-based plasma, high concentrations of carbon (1.44×10^{19} cm^{-3}) and fluorine (2.35×10^{18} cm^{-3}) acceptor-like impurities were introduced to compensate for Si impurities. As a result, the large peak electric field and band bending related to Si impurities at the regrowth interface can be mitigated. Based on fluorine-based plasma treatment, high performance etched-and-regrown GaN-on-Si p-n diodes with high breakdown voltage of ~800V, high current on/off ratio of $\sim10^{11}$, low specific on-resistance ($R_{on,sp}$) of 1.2 $m\Omega \cdot cm^2$ were demonstrated. This work paves the way for selective are p-type doping in GaN by etching and regrowth.

ED-Thu-P11 - Semipolar (11-22) AlN/AlGaN Schottky diodes grown by metal-organic chemical vapor deposition

4. Electronic devices

Junxue Ran[1]
Yiwei Duo[1], Jiankun Yang[1], Junxi Wang[1], Tongbo Wei[1]
[1] Research and Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China

Abstract text: Semipolar (11-22) AlN/AlGaN Schottky diodes grown by metal-organic chemical vapor deposition

Junxue Ran, Yiwei Duo, Jiankun Yang, Junxi Wang, Tongbo Wei

Research and Development Center for Wide Bandgap Semiconductors, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

*E-mail: tbwei@semi.ac.cn

AlN is regarded as one of the most promising ultrawide bandgap (UWBG) semiconductors for fabricating high-voltage and low-loss power devices owing to its large bandgap of 6.2 eV, high thermal conductivity of 340W/mK, high critical breakdown field of 15 MV/cm, and substantially large Baliga's figure of merit (BFOM) [1]. In this work, we demonstrated the semipolar (11−22) AlN/AlGaN quasi-vertical Schottky barrier diodes (SBDs) grown on m-sapphire substrate by metal-organic chemical vapor deposition (MOCVD). The devices exhibit outstanding performance with an ideality factor of 2.05, a barrier height of 1.89 eV, a rectification ratio of more than $\sim 10^8$, the current density is larger than 1A/cm^2 at 9V, the low on-resistance Ron,sp of about 3Ω.cm^2, and the leakage current of about 1.22×10^{-5}mA/cm^2 at 200V reverse voltage. Due to the combination of high quality ultra-wide band gap AlN as the drift layer and Si-dopped AlGaN as current spreading layer, this quasi-vertical (11−22) AlN /AlGaN greatly improves the forward conduction performance compared with AlN lateral SBDs, and greatly reduces the reverse leakage compared with AlGaN lateral SBDs. The results show that (11−22) AlN/AlGaN can effectively mitigate the limited issue of decreasing the on-off loss and improving the blocking capability of UWBG SBDs, which shows great potential for yielding high-performance devices.

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ED-Thu-P12* - 1 kV Ultra-wide bandgap Al0.47Ga0.53N Vertical Junction Barrier Schottky Diodes

4. Electronic devices
Shuhui Zhang[1]
Yuchuan Ma[1], Hang Chen[1], Xiaoping Meng[1], Tianpeng Yang[2], Tingting Mi[2], Xiaowen Wang[2], **Chao Liu**[1]
[1] School of Integrated Circuits, Shandong University, Jinan 250100, China
[2] EpiTop Optoelectronic Co., Ltd. Maanshan 243000, China

Abstract text: We report 1 kV vertical junction barrier Schottky (JBS) diodes, based on ultra-wide bandgap high-Al-composition (HAC) $Al_{0.47}Ga_{0.53}N$-based p-i-n heterostructures, incorporating a p-type GaN/AlGaN termination extension (TE) design. The JBS architecture effectively addresses the Schottky barrier lowering effect at the metal-semiconductor interface, while the TE configuration mitigates the electric field crowding issue near the anode periphery, achieving a record breakdown voltage of 1071 V and dramatically reduced reverse leakage current density compared to conventional designs. Fig. 1(a) and (b) depict the cross-sectional schematic and scanning electron microscope (SEM) image of the epitaxial structures for the JBS diodes. Fig. 1(c) presents the schematic of the vertical JBS diodes, with the fabrication process outlined in Fig. 1(d). Fig. 2(a) shows the forward I-V characteristics of the JBS diodes, exhibiting a high on/off ratio of ~10^7. In Fig. 2(b), the forward I-V and differential specific on-resistance ($R_{on,sp}$) are provided. The V_{on} and differential $R_{on,sp}$ are 2 V and 2.53 $\Omega \cdot cm^2$ for the fabricated devices, respectively. As shown in Fig. 3, the vertical AlGaN JBS diodes exhibit a significantly boosted breakdown voltage to 1071 V from 662 V in the reference vertical AlGaN Schottky barrier diodes (SBDs). Figure 4 presents a benchmarking comparison of $R_{on,sp}$ versus breakdown voltage for the fabricated vertical AlGaN JBS diodes against state-of-the-art III-nitride vertical power SBDs. The developed vertical AlGaN JBS diodes, incorporating a 3 μm-thick HAC AlGaN drift layer, exhibit a record breakdown voltage of 1071 V. This performance surpasses prior AlGaN SBDs and matches the breakdown capabilities of reported GaN-based vertical SBDs, despite the latter utilizing significantly thicker GaN drift layers (typically >5-10 μm). The results highlight the superior material efficiency and enhanced critical electric field tolerance of the HAC-AlGaN architecture in high-voltage power device applications. The fabricated diodes exhibit stable forward-bias operation during 1000-second cyclic on-state (Fig. 5) and off-state (Fig. 6) stress tests. These advancements highlight the viability of vertical high-Al-content AlGaN devices for high-voltage power electronics, offering enhanced performance metrics critical for next-generation energy-efficient systems.

ED-Thu-P13* - Ultra-wide Bandgap Al0.5Ga0.5N vertical PN Memory Diodes

4. Electronic devices
Hang Chen[1]
Shuhui Zhang[1], Yuchuan Ma[1], Tianpeng Yang[2], Tingting Mi[2], Xiaowen Wang[2], **Chao Liu**[1]
[1] School of Integrated Circuits, Shandong University, Jinan 250100, China
[2] EpiTop Optoelectronic Co., Ltd. Maanshan 243000, China

Abstract text: We report the first ultra-wide bandgap $Al_{0.5}Ga_{0.5}N$ vertical PN memory diodes. The schematic and process flow of the vertical AlGaN PN diodes are shown in Fig. 1. XRD and SIMS measurements confirm the thickness, composition, and crystalline quality of the epitaxial structures on sapphire substrates (Fig. 2(a)-(c)). The tilted view SEM image of the fabricated vertical diode is shown in Fig. 2(d). Excellent forward characteristics are achieved, with a high on/off ratio of 10^{10} and a low specific on-resistance of 6.52 $m\Omega \cdot cm^{-2}$ (Fig. 3(a)-(b)). A low reverse breakdown voltage of 47 V is obtained with the intentionally inserted n^+-AlGaN layer (Si: 8×10^{18} cm^{-3}) at the PN junction interface (Fig. 4(a)). The SCLC mechanism dominates the reverse leakage accompanied by the VRH mechanism co-existing at a high reverse bias (Fig. 4(b)-(c)). No discernible variation is observed in the reverse leakage with varied anode sizes (Fig. 4(d)). The reverse current dependence on 1/R for the PNDs in Fig. 4(e) indicates that the leakage current flows within the bulk $Al_{0.5}Ga_{0.5}N$ material instead of across the sidewall. After the initial breakdown, a boosted reverse leakage current is observed, indicating that a conducting path from the anode to the cathode is established (Fig. 5(a)). The threshold shows an evident shift from 4.7 V to 0.8 V, and a hysteresis behavior is observed in the forward double sweep I-V curves (Fig. 5(b)-(c)). The hysteresis phenomenon includes a high resistance state (HRS) and a low resistance state (LRS). Both the set and reset voltage show small fluctuations at 25℃ and 150℃ in 100 cycles, indicating a repeatable switching performance of the memory devices (Fig. 6). Fig. 7 shows the cycling forward performance of the memory diodes with varied temperatures from 25℃ to 150℃. The reset voltage shows a relatively small variation, while the set voltage decreases from 23 V to 16 V. The devices exhibit repeatable forward switching performance from 15 V to 25 V in 100 cycles, indicating a memory behavior in the vertical AlGaN-based diodes (Fig. 8). These results provide promising strategies for developing robust and reliable memory devices based on ultra-wide bandgap III-nitride semiconductors, towards high thermostability and high radiation tolerance for applications in harsh environment.

ED-Thu-P14* - Effect of oxygen partial pressure on the properties of sputtered vertical NiO/GaN heterojunction diodes

4. Electronic devices

Wojciech Hendzelek[1]
Veronica Gao Zhan[1], Jarosław Tarenko[2], Aleksandra Wójcicka[1], Justyna Wierzbicka[1], Marek Wzorek[1], Oskar Sadowski[2], Maciej Kamiński[2], Anna Szerling[1], Paweł Prystawko[3], Michał Boćkowski[3], Izabella Grzegory[3], Andrzej Taube[1]
[1] Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw, Poland
[2] Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw, Poland and Warsaw University of Technology, Institute of Microelectronics and Optoelectronics, Warsaw, Poland
[3] Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw, Poland

Abstract text: The oxide/GaN-based p-n heterojunctions can be employed in vertical GaN-based devices, either as a junction termination extension to mitigate the technological and fundamental problems with low acceptor ionization and non-efficient activation of acceptor species after post implantation annealing. Here in this work we examine the effect of oxygen partial pressure on the properties of sputtered vertical NiO/GaN heterojunction diodes (HJDs). The devices were fabricated on n-GaN epilayers (N_D~$2.5x10^{16}$ cm^{-3}) grown by MOCVD on bulk GaN substrates. The NiO/Ni/Au anodes were fabricated using lift-off photolithography and room-temperature sputtering of 100 nm NiO layers by means of RF magnetron sputtering of ceramic NiO target in O_2/Ar atmosphere under oxygen partial pressure (pO_2) of 0, 10, 20 and 30%. The HJDs with NiO layers deposited with 0% pO_2 were characterised by Schottky-like I-V characteristics with low ideality factor n of ~1.2, turn-on voltage of ~0.55V with forward current over 2kA/cm^2 and breakdown voltage ~400 V (corresponding to parallel plate electric field ~1.8 MV/cm). In contrast, the HJDs fabricated using reactive sputtering possess different conduction mechanisms manifested by higher ideality factor (> 3 @ 0.5V), higher turn-on voltages > 1V and on-state resistance with output current density over 2kA/cm^2 along with much higher breakdown over 600 V (E_{p-p} ~2.3 MV/cm). Annealing at 300°C leads to lowering of reverse leakage current and to the change of reverse current mechanism for HJDs fabricated using reactive sputtering but not to the substantial change of breakdown voltage values. The decrease of output current and turn-on voltages were also observed. These effects can be associated with increasing the resistivity of NiO layers by the decreasing of the native defects responsible for acceptor doping in those layers. Our results shows that with that by optimizing the deposition and annealing parameters, promising results can be achieved that predispose the use of p-NiO layers in the construction of high-voltage GaN-based devices as an alternative to the use of p-GaN layers.

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ED-Thu-P15* - kV-class Vertical GaN Junction Barrier Diodes using Mg Implantation

4. Electronic devices

Dolar Khachariya[1]
Will Mecouch[1], Seiji Mita[1], Azizul Hasan[2], Shashwat Rathkanthiwar[2], Pramod Reddy[1], Ronny Kirste[1], Kacper Sierakowski[3], Grzegorz Kamler[3], Michal Bockowski[3], Erhard Kohn[2], Spyridon Pavlidis[2], Ramon Collazo[2], Zlatko Sitar[2]
[1] Adroit Materials, Cary, NC 27518, USA
[2] North Carolina State University, Raleigh, NC 27695-7919, USA
[3] Institute of High-Pressure Physics, Sokołowska 29/37, 01-142 Warsaw, Poland

Abstract text: Selective area p-type doping has been a major technological hurdle for vertical GaN-based devices. It is an essential building block for a variety of devices, including MOSFETs and junction barrier Schottky (JBS) diodes. Moreover, edge terminations such as junction termination extensions (JTEs) also rely on selective area doping to control the electric field distribution and enable high-voltage operation. Recently, we demonstrated 915 V breakdown GaN JBS diodes using Mg implantation followed by ultra-high pressure annealing (UHPA). In this work, we demonstrate record performance kV-class JBS diodes with R_{ON} of 2.0 mΩ·cm^2 and breakdown voltage (BV) of 1900 V corresponding to a figure of merit of 1.8 GW·cm^{-2}.

A 12 µm thick Si-doped n$^-$-GaN drift layer (N_D ~1×10^{16} cm^{-3}) was grown via MOCVD on an ammonothermal n$^+$-GaN substrate. In addition to the JBS diodes, Schottky diodes (SBD) with and without edge terminations (ET) and p-n diodes were fabricated on the same wafer. To achieve a shallow box profile (~100 nm), Mg ions were implanted at 75 and 25 keV energies with doses of 2×10^{14} and 4.4×10^{13} cm^{-2}, respectively. The activation anneal was performed at 1300°C for 30 min at a high pressure of 400 MPa in N_2 ambient without a capping layer. The device fabrication started with Ni/Au-based p-type Ohmic contact deposition for p-n diodes followed by a contact anneal. Then, Ni/Au-based Schottky contacts were deposited. Finally, a Ti/Al/Ni/Au Ohmic metal stack was deposited on the back side of the n$^+$-GaN substrate.

The IV characteristics of the Schottky and JBS diodes revealed a high rectification ratio of ~10^{12} at ±3 V. An ideality factor of 1.01 was measured for both diodes, which indicates a near-ideal Schottky behavior. Both diodes showed the expected turn-on voltage (V_{ON}) of 0.7 V. The differential R_{ON} for Schottky and JBS diodes was measured to be 1.2 and 2.0 mΩ·cm^2, respectively. While the SBD without ET showed a breakdown at only 250 V, the SBD with Mg implanted p-type ET showed an enhanced BV of 1000 V. Compared to the SBDs, the leakage current in the JBS diode increased mildly till about 1.5 kV followed by a relatively steep increase and a breakdown at 1900 V. This is the highest BV reported value for GaN JBS diodes. The p-n diode fabricated using the implanted p-GaN showed a BV of 2000 V.

ED-Thu-P16* - Engineering Vertical AlGaN Schottky Barrier Diodes: Influence of Stack Design and Anode Alignment on Reverse Leakage Suppression

4. Electronic devices

Avinas N Shaji[1]
Byeongchan So[2], Jovana Malm[2], Vanya Darakchieva[2], Erik Lind[1]
[1] Department of Electrical and Information Technology and Nanolund, Lund University, 22100 Lund, Sweden
[2] Center for III-Nitride Technology, C3NiT-Janzen, Solid State Physics and Nanolund, Lund University, 22100 Lund, Sweden

Abstract text: The influence of device design and the implementation of a novel stack on enhancing performance parameters in vertical AlGaN Schottky Barrier Diodes (SBDs) is investigated. Utilizing a GaN cap layer on an AlGaN drift layer, the surface peak electric field can be reduced. A fabrication process for a GaN/AlGaN heterostructure SBD is presented, targeting improved breakdown voltage and reduced leakage currents by leveraging the superior material properties of AlGaN. The proposed stack design comprises a 50nm GaN cap layer atop a 5µm $Al_{0.05}Ga_{0.95}N$ drift layer, facilitating the engineering of a camel hump-shaped band alignment close to the metal-semiconductor interface. The diodes were fabricated with varying MESA etch depths using an ICP-RIE plasma process and different top-contact (Anode metal) alignments, ranging from 500nm to 10µm from the MESA edge, using optical lithography. A similar batch of quasi-vertical GaN SBD is also fabricated to compare the different diode performances. The resultant 'CAMEL' diodes demonstrate excellent performance metrics, including a slightly higher turn-on voltage(~0.65V) compared to GaN SBD(~0.4V), a high on-off ratio of 10^9, a nearly ideal ideality factor of 1.01–1.05, and a Schottky barrier height of 0.97–1.06eV at room temperature (0.75-0.8eV for GaN SBD). The measured on-resistance is 50 mΩcm² for the CAMEL diode and 10 mΩcm² for the GaN SBD, which correlates with the lower mobility of AlGaN. The leakage-current behavior indicates an increase with deeper MESA etching, highlighting the necessity of a passivation layer to exploit the benefits of MESA designs fully. Additionally, the tight anode alignment from the MESA edge proves helpful at higher reverse bias voltages, indicating an improvement in breakdown performance for the tightly aligned diodes. Overall, this study introduces a promising fabrication strategy for high-performance vertical GaN SBDs, minimizing design complexities while offering valuable insights for next-generation power electronics applications.

Keywords: Gallium nitride, Power electronics, Schottky barrier diode, Camel diode

ED-Thu-P17* - Reversibility of Reverse I–V Degradation Caused by Forward Current Stress in GaN p-n Diodes

4. Electronic devices

Daiki Iwata[1]
Hiroshi Ohta[2], Yoshinobu Narita[1], Takashi Sato[1], Fumimasa Horikiri[2], Tomoyoshi Mishima[2], Takeshi Tanaka[1], Kiyotoshi Iimura[1], Hajime Fujikura[1]
[1] SUMITOMO CHEMICAL Co., Ltd.
[2] Hosei University

Abstract text: It has been reported that forward current stress in GaN p-n diodes increases reverse leakage current. The source of this leakage has been identified as screw-component threading dislocations, but the model explaining the increase in reverse leakage current remains unclear. This report discusses the experiments conducted to elucidate this model and their results.
Using metal-organic vapor phase epitaxy (MOVPE), a p-n structure was fabricated on a free-standing GaN substrate by growing a 9 μm n-GaN layer ([Si]=2.0×10^{16} cm^{-3}), a 500 nm p-GaN layer ([Mg]=1.0×10^{18} cm^{-3}), and a 30 nm p^+-GaN layer ([Mg]=2.0×10^{20} cm^{-3}). After dehydrogenation annealing (N_2 atmosphere, 850 °C, 30 min.), mesas were formed by ICP-RIE, Pd/Ni was deposited as the anode electrode (400 μm), and Ti/Al was deposited as the cathode electrode. Additionally, after forming SOG (Spin on Glass)/SiO_2 as an insulating film, Ti/Al was deposited on the anode electrode as a field plate electrode to fabricate the p-n diode. Devices were characterized as follows: (1) First *I–V* measurement (forward and reverse *I–V* measurement), (2) Forward current stressing at 1 A (795 A/cm^2) for 1 hour, (3) Second *I–V* measurement, (4) Removal of electrodes and insulating film, (5) Dehydrogenation annealing, (6) Reformation of electrodes and insulating film, and (7) Third *I– V*measurement. Each reverse *I–V* measurement was conducted twice.
As reported previously, reverse leakage current increased due to forward current stress, but it recovered to its initial characteristics after re-annealing. Namely, the above degradation is a reversible phenomenon. Furthermore, since the reverse characteristics recovered under the same conditions as dehydrogenation annealing, the partial passivation of Mg in the p-GaN layer due to hydrogen migration along the threading dislocations may be responsible for the increase in reverse current.

[1] T. Narita *et al*., Scientific Reports **12**, 1458 (2022).

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ED-Thu-P18* - High-Performance Vertical GaN-on-GaN Schottky Barrier Diodes with Robust kV-Class Operation

4. Electronic devices

Xinchen Ge[1]
Xiaolu Guo[2], Haoran Qie[2], Yaozong Zhong[2], Xin Chen[2], Hongwei Gao[1], Qian Sun[1], Hui Yang[1]
[1] School of Nano-Tech and Nano-Bionics, University of Science and Technology of China (USTC), Hefei, People's Republic of China
[2] Key Laboratory of Semiconductor Display Materials and Chips, Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences (CAS), Suzhou, People's Republic of China

Abstract text: GaN-based power diodes leverage superior material properties, such as high critical electric field and electron saturation velocity, to achieve high operating voltage and low conduction loss. Vertical GaN-on-GaN homoepitaxial devices outperform lateral/quasi-vertical counterparts on hetero-substrates (e.g., SiC, sapphire, or Si) by enabling thicker, low-defect drift layers, thus fully exploiting GaN power device's potential. This work demonstrates a robust kV-class vertical GaN-on-GaN Schottky barrier diode (SBD) with state-of-the-art performance.

The SBD incorporates an 8 μm homoepitaxial drift layer (6×10^{15} cm^{-3} net doping) and utilizes nitrogen ion implantation on a self-aligned mesa to mitigate electric field crowding. The device achieves a differential specific on-resistance ($R_{on,sp}$) of 1.2 $m\Omega\cdot cm^2$ [Fig. (b)], and the capacitance-voltage (C-V) characterization (1 kHz–1 MHz) exhibits negligible frequency dispersion [Fig. (c)], confirming a high-quality Schottky interface (low interface state density) and a pristine drift layer with minimal impurity contamination. Sentaurus TCAD simulations validate that the self-aligned mesa with nitrogen ion implantation (the termination strategy) effectively suppresses the peak electric field at -1000 V reverse bias, leading to reduced reverse leakage and enhanced BV [Fig. (d)]. With an optimized edge termination design, the device attains a breakdown voltage (BV) of 1012 V [Fig. (e)]. High-temperature reverse tests reveal a retained BV of 830 V at 150°C [Fig. (e)], demonstrating high thermal stability of the GaN SBD. Bidirectional voltage sweeps (0 V to -700 V) show negligible hysteresis [Fig. (g)], while stress tests under -700 V for 50 s reveal no degradation in forward characteristics [Fig. (h)], indicating minimal trapping effects at the interface and the bulk of the device. This robust performance under thermal and electrical stress is attributed to minimized trap/dislocation densities in bulk GaN and optimized fabrication processing, which shows the reliability of the device in high-stress environments. Benchmarking against literature confirms that the device's performance is comparable to some state-of-the-art vertical GaN-on-GaN power diodes [Fig. (h)].

ED-Thu-P19* - Capacitance-Frequency Co-Optimization and Multi-Scenario Applications of High-Power Tri-Channel Trench-Anode GaN Schottky Diodes

4. Electronic devices

Zhengxing Zhang[1]
Kui Dang[1], Menghan Zheng[1], Mengjiao Xiang[1], **Kai SU**[1], Jincheng Zhang[1], Yue Hao[1]
[1] Xidian University,School of Integrated Circuits, Xi'an,China

Abstract text: This study achieves synergistic optimization of high-frequency response, power handling, and current density in tri-channel trench-anode GaN Schottky barrier diodes (SBDs) through cathode-anode spacing modulation (1–3 μm). A tri-channel heterostructure was epitaxially grown using an AlN buffer layer with alternating GaN/AlN/$Al_{0.25}Ga_{0.75}N$ layers (sheet resistance: 146.4 Ω/sq), enabling the fabrication of microwave diodes. The 1 μm-spaced device exhibits a peak current density of 2.97 A/mm at 5 V bias (specific on-resistance: 1.01 Ω·mm), though its breakdown voltage is constrained by leakage. Extending the spacing to 2 μm maintains a high current density of 2.34 A/mm (78.8% of the 1 μm device) while reducing junction capacitance to 582.6 fF/mm. Combined with a 1.33 Ω·mm on-resistance, this yields a cutoff frequency of 205 GHz, with leakage currents below 100 μA up to 80 V—representing a 3–5× current density improvement over conventional planar GaN SBDs. Further increasing the spacing to 3 μm achieves a breakthrough breakdown voltage of 197 V (leakage <100 μA at 140 V) while retaining 2.03 A/mm current density and 1.86 Ω·mm on-resistance. A 640.7 fF/mm capacitance enables 134 GHz cutoff frequency, demonstrating unique advantages for high-voltage power systems.

The tri-channel architecture leverages AlN interlayers to induce high-density 2DEG (>2×10^{13} cm^{-2}) for robust current transport, while the trench-anode design mitigates current degradation at larger spacings. The tri-channel architecture leverages AlN interlayers to induce high-density 2DEG (>2×10^{13} cm^{-2}) for robust current transport, while the trench-anode design reduces turn-on voltage and enhances device reliability. The 2 μm device, with 205 GHz cutoff frequency and >2 A/mm current density, emerges as an ideal candidate for X/Ku-band (8–18 GHz) RF front-ends. The 3 μm variant, balancing 197 V breakdown and 134 GHz frequency response, targets automotive fast-charging systems and radar power modules. This work systematically reveals the correlation between cathode-anode spacing and the capacitance-frequency-breakdown trade-off, providing a roadmap for future optimization via field-plate designs to suppress edge leakage.

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ED-Thu-P20* - Effect of compensation on the performance of AlN-based heterojunction p-n diodes

4. Electronic devices

Cristyan Quiñones[1]
Dolar Khachariya[2], Pramod Reddy[2], Shashwat Rathkanthiwar[1], Ronny Kirste[2], Seiji Mita[2], Erhard Kohn[1], Ramón Collazo[1], Zlatko Sitar[1]
[1] Department of Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina 27695, USA
[2] Adroit Materials Inc., 2054 Kildaire Farm Road, Cary, North Carolina, 27518, USA

Abstract text: Aluminum Nitride (AlN) is an attractive material for high-temperature kV-class power devices due to its ultra-wide bandgap, high breakdown field, thermal conductivity, and temperature stability. However, realizing such devices in AlN is complicated by the difficulty in doping. Particularly, increasing the doping past a critical concentration induces the formation of compensating point defects that limit the conductivity. In this work, we study the effects of self-compensation on the performance of AlN heterojunction p-n diodes.

Using metalorganic chemical vapor deposition, quasi-vertical p-n diode structures were grown on c-oriented, single crystal, bulk AlN wafers. The device structures consisted of a 2 μm-thick n-AlGaN cathode, a 1 m thick n-AlN drift and a thin p-AlGaN anode. To study the effects of self-compensation on device performance, structures were grown with moderate (1×10^{18} cm^{-3}) and heavy (5×10^{19} cm^{-3}) Si doping in the AlN drift layer. Circular mesas were defined using photolithography and reactive ion etching. Cathode ohmic contacts consisted of a large area Cr/Ti/Al/Ti/Au metal stack and annealed at 950°C for 30 s under a N_2. Anode ohmic contacts consisted of a Ni/Au metal stack annealed at 600°C for 10 min in air.

The effect of self-compensation on device performance was characterized by comparing current-voltage (*I-V*), capacitance voltage (*C-V*) and electroluminescence (EL) data of devices with moderate and heavy doping. The C-V data shows the heavily doped diodes have a net doping concentration three orders of magnitude lower than the actual Si concentration. The moderately doped diodes show an order of magnitude higher net doping, despite having lower Si. This indicates high compensating defect concentrations in the heavily doped samples. The moderately doped diodes show better performance, with an order of magnitude higher ON-state current. Further, the heavily doped samples show higher leakage current and strong non-linearity in the forward bias, indicating that the compensators play a role in the ON-state conduction. The best performing devices show densities >3.5 kA/cm^2 and constant differential specific ON-resistance of 1.1 $m\Omega\cdot cm^2$. The effects of abrupt vs. graded anode structures will also be discussed. These results highlight that understanding point defect formation is critical for further advancing AlN electronic device technology.

ED-Thu-P21* - Fully Vertical Si-doped AlN SBDs with Crack-free AlN Film on Si(111)

4. Electronic devices

Haicheng Cao[1]
Mingtao Nong[1], Ying Wu[1], Xiaohang Li[1]
[1] Computer, Electrical and Mathematical Science and Engineering (CEMSE) Division, King Abdullah University of Science and Technology (KAUST)

Abstract text: Aluminum Nitride (AlN) has emerged as a promising candidate for high-power electronics under high-temperature conditions, attributed to its exceptional thermal conductivity, high critical breakdown field, and remarkable stability. In terms of power handling capabilities, fully vertical devices offer more uniform electric field distribution and compactness compared to lateral structures. Notably, fully vertical power devices based on Si substrates inherently possess a cost advantage and have been successfully implemented in commercial GaN power devices. However, the development of AlN-based vertical devices on Si was impeded by lattice and thermal expansion mismatches, inducing severe tensile stress leading to film cracking. Moreover, Si doping further escalates the internal tensile stress within AlN. In this work, we demonstrate crack-free heteroepitaxial growth of 500 nm Si-doped AlN on Si(111) using boron pretreatment, ultimately enabling the first functional fully vertical AlN-on-Si Schottky barrier diodes (SBDs).

A 500-nm-thick AlN layer with Si doping concentration of 1×10^{18} cm^{-3} was grown via MOCVD. High-resolution X-ray diffraction revealed narrow rocking curve FWHM values of 0.21° for (002) and 0.36° for (102) planes, accompanied by surface roughness <0.5 nm. The fabricated vertical SBD features backside n-Si ohmic contact and frontside Pt/Au Schottky contact. I-V characterization demonstrated that the device exhibited significant rectification characteristics even at extremely high temperatures (up to 400°C). It displayed ideal Schottky contact (n=1.03) at 300 °C, with a barrier height of 2.81 eV, and an Ion/Ioff ratio exceeding 1×10^{5}. The device's reverse breakdown voltage reached 169 V, which was still 132 V even at a high temperature of 200 °C. The calculated peak breakdown electric field reached 6.76 MV/cm (the average breakdown field is 3.38 MV/cm) at room temperature (RT), 5.28 MV/cm (the average breakdown field is 2.64 MV/cm) at 200 °C, far exceeding that of GaN-on-Si devices, demonstrating the great potential of AlN-on-Si in the field of high-voltage power devices for high temperature application.

ED-Thu-P22 - Precise ablation of gallium nitride heterostructures with a femtosecond laser for microelectronics applications

4. Electronic devices

Simonas Indrišiūnas[1]
Laimis Zubauskas[1], Justinas Jorudas[2], Irmantas Kašalynas[2], Paulius Gečys[1]
[1] Center for Physical Science and Technology (FTMC), Department of Laser Technologies, Vilnius, Lithuania
[2] Center for Physical Science and Technology (FTMC), Department of Optoelectronics, Vilnius, Lithuania

Abstract text: Heterostructures containing gallium nitride (GaN) remain widely used in high-power and high-frequency applications [1]. Furthermore, microelectronics applications require precise surface processing technologies capable of ensuring sub-micron scale resolution and minimizing the time needed for element post-treatment. One of the most universal technologies to meet these requirements is direct laser ablation with femtosecond pulse durations [2]. The mask-less direct laser micromachining can be auxiliary tool and expand usage of recessed electric contacts in nitride-based semiconductor heterostructures [3].

The ablation resolution and accuracy of laser-ablated structures are limited by diffraction phenomena, laser beam spot size and penetration depth in the material. Fortunately, transitioning to wavelengths in the UV range could improve laser beam absorption and facilitate removal of layers thinner than 100 nm [4].

In this study, we investigated the influence of femtosecond laser beam wavelength on the ablation depth resolution of GaN samples. A number of ablation processes were conducted to find the thinnest removable layer values with laser radiation at wavelengths of 1030, 515, and 343 nm. The shortest wavelength enabled the ablation of structures over three times thinner than those at 1030 nm, achieving a depth of approximately 40 nm. In addition, the optimized regimes developed for 2D sample structuring will be discussed as a first step in the auxiliary direct laser micromachining of microelectronic devices.

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ED-Thu-P23 - High performance GaN-on-sapphire Schottky Detector with SNR over 2×10^6

4. Electronic devices

Zixiao Sun[1]
Kai Su[1], Yachao Zhang[1], **Jinfeng Zhang**[1], Zeyang Ren[1], Yu Fu[1], Yue Hao[1], Jincheng Zhang[1]
[1] State Key Laboratory of Wide Bandgap Semiconductor Devices and Integrated Technology, Xidian University, Xi'an, China

Abstract text: Planar GaN Schottky barrier diode (SBD) was fabricated based on 15-μm-thick GaN layer grown on sapphire substrate and used as X-ray detector with the finger length, width, and interspace of 2 mm, 25 μm and 30 μm. Under 120 keV X-ray radiation, the signal-to-noise ratio (SNR) reached over 3000 at reverse bias, and the sensitivity of 19.14 mC/Gy·mm³ at -50 V and linearity of 0.9301±0.0196 at -10 V were achieved for the dose rate range of 0.11 to 6.28 Gy/min. What's more, X-ray detection at +10 V (0.33 V/μm) was achieved based on low dark current with record high SNR of 2.19×10^6, and sensitivity of 2.39 C/Gy·mm^3, and linearity of 0.965±0.008 on the same dose rate range. The low dark current originated from high-quality undoped GaN epitaxy and strengthened by post-Schottky rapid thermal annealing at 450 ℃ in N_2 and passivation was very important to enhance the detector performance. After Schottky contact annealing the dark current decreased nearly a half, and was 3.76 nA at -10 V and 23.2 nA at -50V. This could be due to annealing induced reduction of interface states and surface traps. This GaN-SBD X-ray detector is very promising for future applications in aerospace, medical diagnosis, industrial testing, safety inspection, and art research.

ED-Thu-P24* - New Interpretation of Fermi-level Pinning Behavior in P-type GaN MOS Capacitors via Temperature-Dependent C-V measurements

4. Electronic devices

Fumiyuki Sei[1]
Kenji Ito[2], Masahiro Horita[3], Tetsu Kachi[2], Jun Suda[3]
[1] Department of Electronics, Nagoya University, Nagoya 464-8601, Japan
[2] IMaSS, Nagoya University, Nagoya 464-8601, Japan
[3] Department of Electronics, Nagoya University, Nagoya 464-8601, Japan; IMaSS, Nagoya University, Nagoya 464-8601, Japan

Abstract text: Understanding and controlling the GaN MOS interface are essential. Recently, many groups have reported the presence of high-density interface defects (hole traps) near the valence band edge in GaN MOS structures. In *C-V* measurements of p-GaN MOS capacitors, a large plateau corresponding to Fermi-level pinning has been observed, preventing the achievement of hole accumulation. This phenomenon is thought to be caused by a high interface-trap density (D_{it}); however, the details of Fermi-level pinning remain unclear.

A Mg-doped p-type GaN layer (5×10^{17} cm^{-3}, 1 μm) was grown on a p^+-GaN/n^+-GaN/n^+-GaN substrate by MOVPE. An AlSiO layer (Si: 21%, 40 nm) was deposited using plasma-enhanced atomic layer deposition[1]. Post-deposition annealing was performed at 400°C for 30 minutes in N_2. Al was used as the gate electrodes.

Dual-sweep *C-V* measurements (5 V → -15 V → 5 V) were conducted at 30°C. A plateau (from -3 V to -15 V), attributed to Fermi-level pinning (E_V + 1.1 eV) due to hole trapping, was observed, consistent with previous reports. The *C-V* curves remained unchanged regardless of the sweep rate. Furthermore, *C-V* measurements with varying sweep ranges showed that most of the shift caused by hole trapping was not recovered. However, trapped holes could be released by light irradiation.

To investigate the activation energy of hole emission, *C-V* measurements were conducted at 200°C. The curves at 30°C and 200°C were nearly identical, suggesting that most trapped holes are not thermally emitted. Repeated *C-V* measurements without recovery time were performed at both 30°C and 200°C. At 30°C, almost no trap release was observed, i.e., the 5th cycle showed no hysteresis and closely matched the back sweep of the 1st cycle. In contrast, at 200°C, a hysteresis loop appeared for all cycles, indicating thermal emission of roughly 1/5 of trapped holes. These results suggest the existence of two distinct types of hole traps for the large plateau: those released at 200°C and those that remain trapped. We speculate that the former is D_{it} as previously suggested, while the latter consists of oxide traps (near-interface traps).

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ED-Thu-P25 - High Sensitivity AlGaN/GaN Magnetic Sensing: Split-Electrode Sensor Array for Ultralow Field Detection at 2.4 uT

4. Electronic devices

Lingxi Xia[1]
Yung C. Liang[1]
[1] National University of Singapore, Singapore

Abstract text: AlGaN/GaN based devices became increasingly important in the automotive and mobility sectors, especially for applications in advanced driver assistance systems. This growing role drives the need for comprehensive sensor integration using AlGaN/GaN technology. Critical vehicle functions such as steering assistance, pedal position sensing and gear shift switches require highly sensitive and stable magnetic sensors, making AlGaN/GaN based sensors essential for next-generation automotive solutions [1].

In this work we demonstrate enhanced magnetic sensing performance using AlGaN/GaN based split electrode sensor array for ultralow field detection. The sensor design leverages a split electrode architecture to capture the magnetic field induced current imbalance (ΔI) which is directly proportional to the total current (I_{tot}) and the magnetic field strength (B) [2] [3]. The minimum detectable field (B_{min}) is ultimately limited by the signal to noise ratio.

Previous work of channel geometry and increased I_{tot} in single devices achieved a B_{min} of 19 μT at high bias current near saturation [4]. Although the magnetic signal can be amplified, the noise level also increases significantly with this approach. The current design of sensor array with multiple cells significantly enhances the magnetic signal output, and at the same time, lowers the internal resistance and reduces the noise floor. We evaluated devices ranging from a single sensor to arrays with 7, 19, 32 and 61 sensor cells. Experimental results show that while a single sensor exhibits a B_{min} of 48 μT, a 19-sensor array reduces B_{min} to 4 μT and a 61-sensor array achieves a detection limit as low as **2.4 μT**. An FFT-based denoising process further validates the low noise performance of our sensor arrays.

These findings underscore the potential of sensor array to address challenges in ultralow magnetic field sensing and pave the way for their integration into advanced power electronic and automotive systems that require precise field detection and control.

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