dgkk DEMBE 2025

ABSTRACT BOOK

Joint Workshop of the Deutsche Gesellschaft für Kristallwachstum und Kristallzüchtung (DGKK) on Epitaxy of III-V Semiconductors and the German MBE Workshop (DEMBE)

December 3-5, 2025 Magdeburg

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Welcome note

Dear attendees of the DGKK/DEMBE workshop in 2025!

A warm welcome in Magdeburg, the capital of Saxonia-Anhalt at Elbe river. The epitaxy business has a home here at the Otto-von-Guericke-University Magdeburg and we are very pleased to host you in the Gesellschaftshaus Magdeburg from Dec. 3rd to Dec. 5th 2025 for our annual workshop. We hope you will enjoy a well organized meeting, giving you space and time to talk and exchange with colleagues, friends and industrial partners.

Epitaxy remains a challenge to everyone in the field despite the huge progress seen in sources, reactor equipment and instrumentation for in-situ and ex-situ characterization. While these advances are inevitable, they only shift our focus to higher precision of the growth of matured materials and towards more complex structures and growth approaches. At the same time, novel materials and novel growth techniques are always appearing on the horizon, promising even more sophisticated epitaxy. This annual workshop has always been and will hopefully always be a meeting where information exchange is enabled between different material families, growth techniques and senior and young researchers to enable steady progress in understanding and execution of epitaxial growth.

We have put together a mix of 4 invited talks surrounded by contributed talks running in two parallel sessions aiming at focussed discussions on current materials issues. Please use coffee and lunch breaks to connect with exhibitors to learn about their products and perhaps current issues with supply and delivery in these changing times.

Running this series of workshops would not be possible without generous sponsoring by many industrial partners among which are AIXTRON, COHERENT, EPISERVE, kSA, RIBER, and SEI. But also our exhibitors complement our workshop and inspire us with new developments and improvements that help us to conduct high-level research. We, the organizers, are very much indebted to them as their reliable support of the workshop well ahead of time takes a lot of burden from us.

With this, we wish you a pleasant stay, stimulating discussions and talks, and an enjoyable evening during our evening reception on Thursday, Dec. 4th.

André Strittmatter and Armin Dadgar

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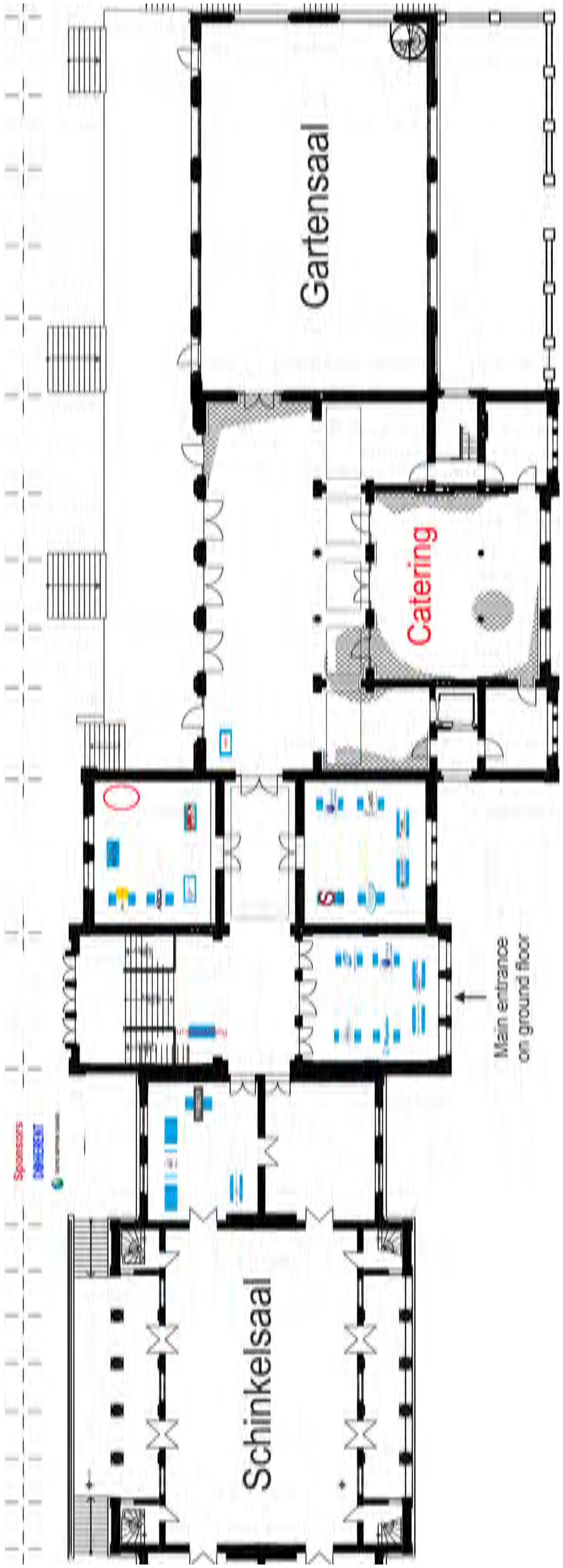
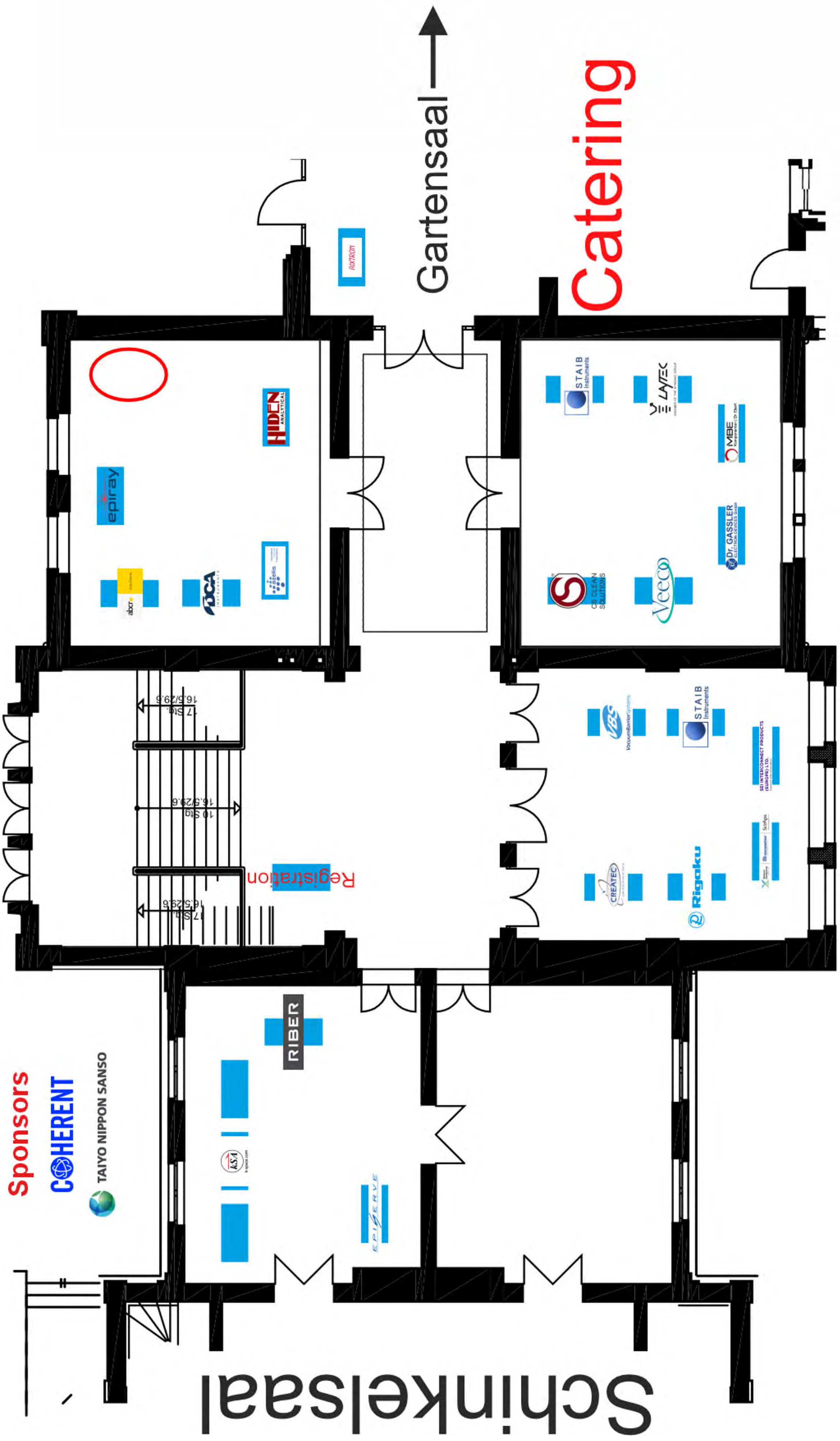


Exhibiting companies



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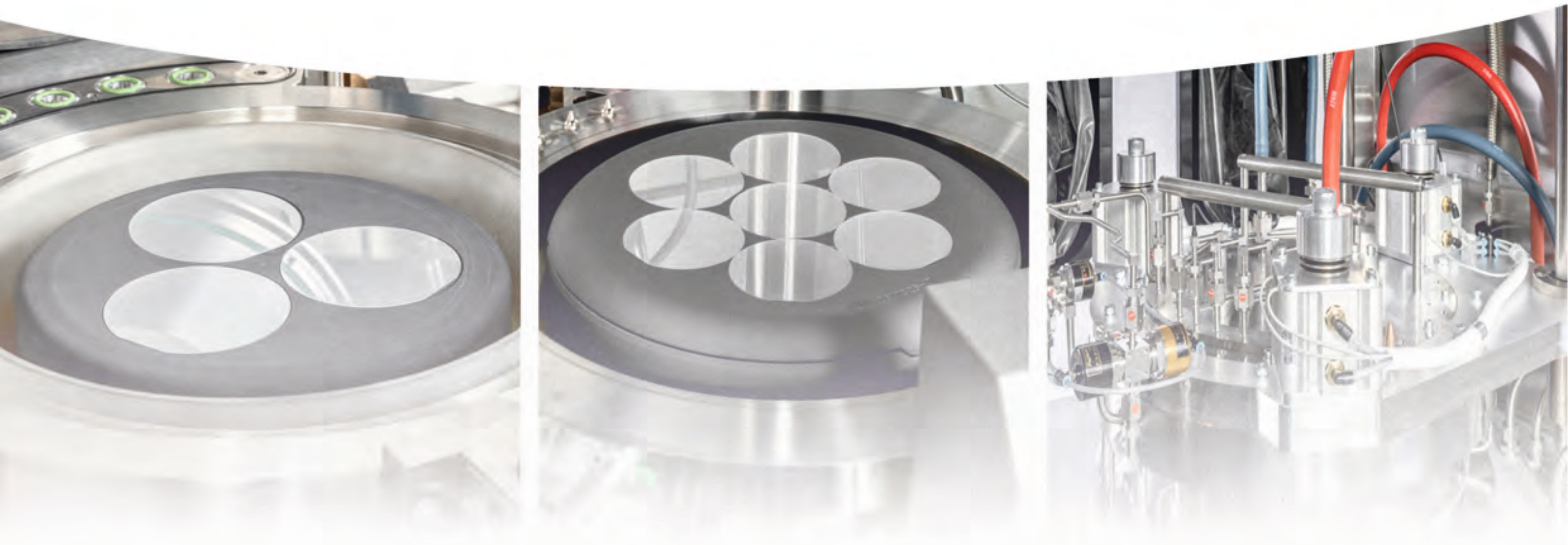

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Program overview of the joint Workshop of the DGKK on Epitaxy of III-V Semiconductors and German MBE Workshop (DEMBE)

Wednesday, December 3rd 2025

12:00-13:00	Arrival and a light meal	
	Gartensaal	**Schinkelsaal**
13:00-13:10	Welcome	
	In(Ga)As Quantum Dots	**Nitrides: Characterization**
13:10-13:30	Unfried - MOVPE-grown C-Band Emitting InAs Quantum Dots on a Ge-Buffered Si (001) Substrate	Kowallik - Determination of optical losses in AlGaN-based multimode waveguides
13:30-13:50	Limame - Fabrication of a III/V SiO_2/SiN hybrid cavity incorporating a single Stark tunable (In,Ga)As quantum dot for high rate single photon generation	Zameshin - Analytical X-ray Solutions for thin film and wafer analysis
13:50-14:10	Oberle - Integration of quantum dot-based single-photon sources onto silicon photonic platform using micro-transfer printing	Dreyer - Nano-characterization of structural and optical properties of a red-emitting InGaN-LED
14:10-14:30	Gaur - Scalable Quantum Photonic Platform Based on Site-Controlled Quantum Dots Coupled to Circular Bragg Grating Resonators	Grieger - Study of defect transitions by surface photovoltage spectroscopy
14:30-14:50	Badura - Capacitance–Voltage Spectroscopy for Characterizing Quantum Dot Electronic Structure and Epitaxial Layer Quality	Ibrahimkutty - High-Resolution XRD Analysis of Compound Semiconductor Materials Using the Rigaku SmartLab Diffractometer
14:50-15:50	Coffee break	
15:50-16:30	**Invited: Eickhoff - Molecular beam epitaxy of group III-sesquioxides: What's so special?**	
	Arsenide & Phosphide based QDs and NWs	**Other Materials**
16:30-16:50	Reuter - Droplet etched quantum dots in the $InP/In_yAl_{1-y}As/In_xGa_{1-x}As$ system for single photon emission in the optical C-band	Zittel - Chemical Vapor Deposition of Copper Iodide
16:50-17:10	Anderson - Generation Waves: Exploring Spatial Modulations of InAs QDs' Structure and Properties for Telecom O-Band Applications	Malindretos - Molecular Beam Epitaxy of 2H-TaS_2 few-layers on GaN(0001)
17:10-17:30	Sauer - Etching of Nanoholes for the Growth of site-controlled InAs Qds in the telecom C-band	Karg - Growth of rutile GeO_2 by plasma-assisted suboxide molecular beam epitaxy
17:30-17:50	Bohlemann - Towards stable passivation layers on III-V-semiconductor nanowires for photoelectrochemical water splitting applications	Hoffmann - In-Situ monitoring of metal-induced redox reactions on $SrTiO_3$ by laser reflectometry and x-ray photoelectron spectroscopy
17:50-20:00	Snacks, Drinks, Company exhibition	

Thursday, December 4th 2025

	Gartensaal	Schinkelsaal
9:00-9:40	**Invited: Semond - Molecular Beam Epitaxy of Niobium Nitride III-N/NbN Hybrid Heterostructures**	
	Nitrides: Preparation	**Arsenides & Phosphides : Growth & Characterization**
9:40-10:00	Bilke - Towards a clean GaN/GaN regrowth interface	Kleinschmidt - Measurement of PEC devices by in situ TRPL
10:00-10:20	Brunner - GaN-on-GaN interface optimization for III-Nitride electronic device structures	Schygulla - MOCVD Reactor Quality Monitoring Using Double-Heterostructures
10:20-10:40	Kreuzer - High-Temperature Annealing of AlN as Template for UV LEDs and Power Electronics in CO and NH3 Containing Atmospheres	Shekarabi - TiO_2 Growth and Band Alignment on GaInP(100): Comparing P-rich to Oxidized Surfaces
10:40-11:40	Coffee break	
	Arsenides : Growth	**Nitrides : Growth**
11:40-12:00	Henksmeier - Remote epitaxy of universal quasi-substrates	Schörmann - AlScN pseudo-substrates for lattice-matched growth of high-In-Content InGaN targeting red micro-LEDs
12:00-12:20	Darwish - MOVPE growth of InGaAs strain-balanced multi quantum well 0.66-eV absorber material for thermophotovoltaic applications	Rodmann - Porous GaN-Interlayers grown by MOVPE
12:20-12:40	Kamath - Epitaxial Development of Resonant-Enhanced Interband Cascade Infrared Photodetectors for Mid-Infrared Gas Sensing Based on Ga-Free Superlattices	Grigoletto - Influence of AlN/Sapphire Substrate Miscut on the Morphology and Threshold of 265 nm AlGaN DQW Laser
12:40-13:00	Vogt - Growth and Applications of InAs/GaSb T2SLs and Development of Ga-free InAs/InAsSb T2SLs by Molecular Beam Epitaxy	Beckmann - Progress on AIXTRON's 200 mm InGaN-based Micro-LED Program
13:00-14:10	Lunch	
	MBE of InGaAs QDs	**In-situ Growth Monitoring**
14:10-14:30	Avdienko - MBE growth of electrically tunable asymmetric InAs/InGaAs QD-molecules emitting in O-band	Haberland - About the accuracy of in-situ metrology: Comparison of in-situ measured layer thicknesses in MOVPE with cross-section STEM
14:30-14:50	Patane - Molecular Beam Epitaxy of Electrically Chargeable and Tunable Telecom C-Band Quantum Dots	Hasanli - Advantages and Limitations of In-Situ Curvature Measurements During MBE Growth
14:50-15:10	Kersting - Low-density InAs quantum dots for telecom O-band single-photon emission	Bastiman - Toward Agentic AI for MBE: A Unified AI, RHEED, and Control Software for Rapid GaN Growth
15:10-15:30	Krüger - Importance of Aluminium Quality for High-Quality Quantum Emitter	Grutke - Optical In-Situ Response During Pulsed III–V Nucleation on Silicon

15:30-16:10	**Invited: Heuken - Review on several years of Innovation in Metalorganic Chemical Vapor Phase Deposition (MOCVD)**	
16:10-17:10	Coffee break	
		InGaAs-based Lasers
17:10-17:30	Preparation for Dinner	Noack - Gain and Absorption of MOVPE grown InGaAs Quantum Dot based Laser Devices for Emission in the NIR
17:30-17:50		Rühle - First Investigations of ASE for a seeded 1064 nm MEXL
17:50-18:10		Mukhangali - Single-layer high-density quantum dot lasers at 900-920 nm for low repetiton rate monolithic mode-locking
18:10-18:30		Baraz - In-situ EBL Fabrication and Characterization of Highly Homogeneous Micropillar Laser Arrays for Neuromorphic Computing Applications
19:00	Dinner	

Friday, December 5th 2025

	Gartensaal	Schinkelsaal
9:00-9:40	**Invited: Weyers - Broad range of specs, low volume: efficient production of device heterostructures in MOVPE**	
	Cubic GaN	**Nitrides on TiN**
9:40-10:00	As - Remote Epitaxy of cubic Gallium Nitride on 3C-SiC (001) Substrates using amorphous Carbon Films	Kaynar - Epitaxial growth and crystalline phases of $Ti_{1-x}Al_xN$ on Si (111) using cubic TiN and wurtzite AlN buffer layers
10:00-10:20	Zscherp - Mechanism of self-assembled cubic InGaN/GaN quantum well formation and bulk InGaN layers in metal-modulated molecular beam epitaxy	John - Epitaxial integration of GaN platelets and thin films on metallic TiN using a MBE-MOVPE hybrid approach
10:20-10:40	Jentsch - Cubic InGaN for Red Emission: Improved Phase Stability and Emission Properties by Metal-Modulated Epitaxy	Dadgar - True vertical GaN diode on TiN-on-Si(111)
10:40-11:20	Coffee break	
	Sputter Epitaxy and Local Epitaxy	**Nitrides : Growth & Characterization**
11:20-11:40	Hörich - In-situ measurements in reactive sputter epitaxy	Bertram - Nanoscopic Insights into the Structural and Optical Properties of the Active Region of Far-UVC-LEDs: Impact of Composition Gradient in Polarization Doping
11:40-12:00	Ott - Magnetron Sputter Epitaxy of AlN and GaN on up to 200 mm Substrates	Abbas - Bravais class like Hexagons based micro-/nano UV optical cavity for next-generation opto-electronics
12:00-12:20	Bruckmann - Progress in local epitaxy of GaAs on Si by Laser-assisted MOVPE	Koch - Following Charge Carrier Transport in Freestanding Core–Shell GaN Nanowires on n-Si(111) Substrates
12:20-13:20	Goodbye, Lunch bag	

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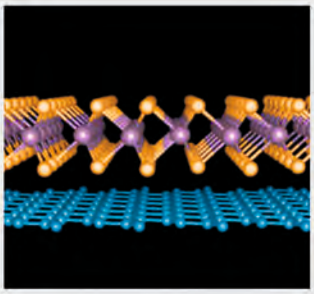

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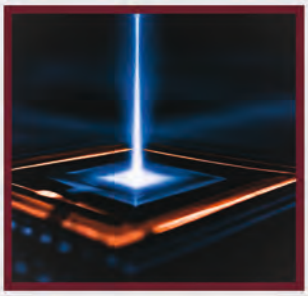

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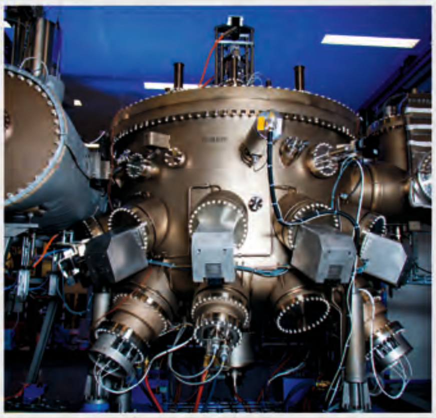

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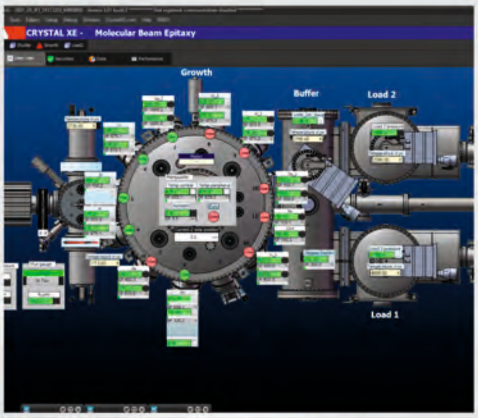

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Wednesday, December 3rd 2025, 13:00-14:50

Gartensaal

13:00-13:10	Welcome

In(Ga)As Quantum Dots

13:10-13:30	Unfried - MOVPE-grown C-Band Emitting InAs Quantum Dots on a Ge-Buffered Si (001) Substrate
13:30-13:50	Limame - Fabrication of a III/V SiO_2/SiN hybrid cavity incorporating a single Stark tunable (In,Ga)As quantum dot for high rate single photon generation
13:50-14:10	Oberle - Integration of quantum dot-based single-photon sources onto silicon photonic platform using micro-transfer printing
14:10-14:30	Gaur - Scalable Quantum Photonic Platform Based on Site-Controlled Quantum Dots Coupled to Circular Bragg Grating Resonators
14:30-14:50	Badura - Capacitance–Voltage Spectroscopy for Characterizing Quantum Dot Electronic Structure and Epitaxial Layer Quality

MOVPE-grown C-Band Emitting InAs Quantum Dots on a Ge-Buffered Si (001) Substrate

J. Unfried[1], P. Vijayan[1,*], M. Jetter[1] and P. Michler[1]
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The integration of III-V materials, known for their excellent optical emission properties [1], with silicon, which enables large-scale, low-loss passive circuitry [2], provides an effective route toward highly functional photonic integrated circuits (PICs). Among various methods, monolithic integration is the most desirable due to its economic and high-density advantages. However, direct growth of III-V materials (e.g., GaAs) on silicon is challenging because of the large lattice mismatch and polarity differences [3], typically requiring a thick GaAs buffer layer to relieve strain and reduce dislocations. A cost-effective alternative is to replace much of this thick buffer with a thin, low-defect-density Germanium layer. Germanium, with a lattice constant nearly matching that of GaAs (0.07% at 300 K) [4], serves as an ideal interfacial layer for III-V integration. Numerous III-V devices have been integrated onto silicon using ultra-thin, relaxed Ge layers, mainly for lasers and photodiodes [5]. However, only a few studies have explored Germanium virtual substrates (GeVS) for integrating III-V quantum dots (QDs) for single-photon applications, and, to our knowledge, no work has demonstrated telecom C-band-emitting III-V QDs on silicon using this approach. Here, we report the growth of telecom C-band-emitting InAs QDs on a Ge-buffered Si (001) substrate using metal-organic vapor phase epitaxy (MOVPE).

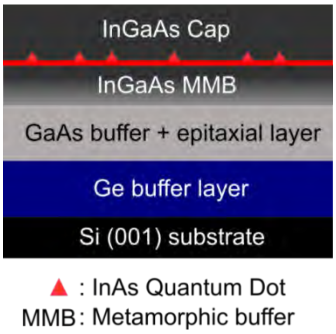

Fig. 1: Schematic drawing of a MOVPE-grown C-Band Emitting InAs Quantum Dots on a Ge-Buffered Si (001) Substrate

[1] Tanabe, K., Watanabe, K. & Arakawa, Y. *Sci Rep* 2, 349 (2012).
[2] Chen, S., Li, W. et al., Nature Photonics 10, 307-311 (2016).
[3] Bogumilowicz, Y., Hartmann, J. M. et al., Journal of Crystal Growth, 180-187 (2016).
[4] Cooper A. S., Acta Crystallopraphica 6, 578-582 (1962).
[5] Michel, J., Liu, J. & Kimerling, L. C. Nature Photonics 4, 527-534 (2010).

Fabrication of a III/V–SiO_2/SiN hybrid cavity incorporating a single Stark-tunable (In,Ga)As quantum dot for high-rate single-photon generation

I. Limame[1], Kartik Gaur[1], Sarthak Tripathi[1], A. Koulas-Simos[1], C. C. Palekar[1], S. Reitzenstein[1]

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The advancement and widespread adoption of quantum photonic technologies, particularly secure quantum communication based on semiconductor quantum dots (QDs), fundamentally depend on the on-demand generation of high-quality quantum light. Emission of single photons with high brightness, purity, and indistinguishability is essential for scalable quantum networks and coherent quantum information processing. To meet these demands, ultrafast modulation of quantum emitters has become increasingly important, enabling high-speed operation.

However, the achievable clock rate of single-photon emission in QD systems is fundamentally limited by their inherently slow radiative decay time, typically in the nanosecond range. To overcome this limitation, recent efforts have focused on integrating single QDs into photonic nanostructures that enhance light–matter interaction, resulting in an increased Purcell factor and accelerated emission dynamics [1]. Despite these advances, such approaches often rely on complex wire-bonding and alignment procedures that are labor-intensive and difficult to scale, hindering large-scale integration of QD-based quantum photonic circuits.

In this work, we demonstrate a scalable hybrid cavity platform integrating a single Stark-tunable QD, embedded within a p-i-n diode structure, into a light-confining resonator composed of an epitaxially grown III/V bottom mirror and a PECVD-deposited dielectric top distributed Bragg reflector (DBR) [2]. This hybrid design enhances the spontaneous emission rate of the QD via the Purcell effect, thereby reducing its radiative lifetime. Additionally, deterministic positioning of the QD within a photonic structure using in-situ electron-beam lithography (EBL) [3] ensures precise spatial alignment of the emitter with the optical mode, significantly improving both photon-extraction efficiency and emission coherence.

Overall, this approach represents a significant step toward realizing scalable, high-brightness, and coherent quantum light sources, providing a robust foundation for next-generation integrated quantum photonic technologies.

[1] L. Rickert et al., ACS Photonics 12 (1), 464–475 (2025)

[2] K. Gaur et al., Appl. Phys. Lett. 124, 041104 (2024)

[3] S. Rodt and S. Reitzenstein, Nano Ex. 2, 014007 (2021)

Integration of quantum dot-based single-photon sources onto silicon photonic platform using micro-transfer printing

S. Oberle,[1] P. Vijayan,[1] S. L. Portalupi,[1] M. Jetter,[1] and P. Michler[1]
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Silicon photonics for telecommunication applications has garnered much attention recently. The optical transparency and the large refractive index contrast of silicon in the telecommunication wavelengths allow the implementation of high-density photonic integrated circuits. One disadvantage of silicon photonics is the lack of a native light source due to the indirect bandgap nature of silicon. One potential solution is the integration of III-V material, which offers outstanding optical emission properties, on a silicon platform. The direct growth of III-V materials on silicon is economically favorable and therefore the most desired approach. However, it is challenging because of the material polarity difference, which leads to anti-phase domains and the significant lattice mismatch between GaAs and silicon, which generates misfit and threading dislocations [1].

An alternate approach for large-scale integration is through hybrid integration of III-V structures using micro-transfer printing. Our group has previously developed a thin MOVPE grown InGaAs metamorphic buffer, on which InAs quantum dots (QDs) emitting in the telecom C-band can be grown [2]. Here, we report our approach to designing and fabricating structures for the hybrid integration of these QDs onto a silicon platform using micro-transfer printing. This process imposes several demands onto the epitaxial growth: Firstly, a release layer is required to selectively underetch the structures. Additionally, the strain in the metamorphic buffer can lead to bending of the fabricated structures, which must be avoided.

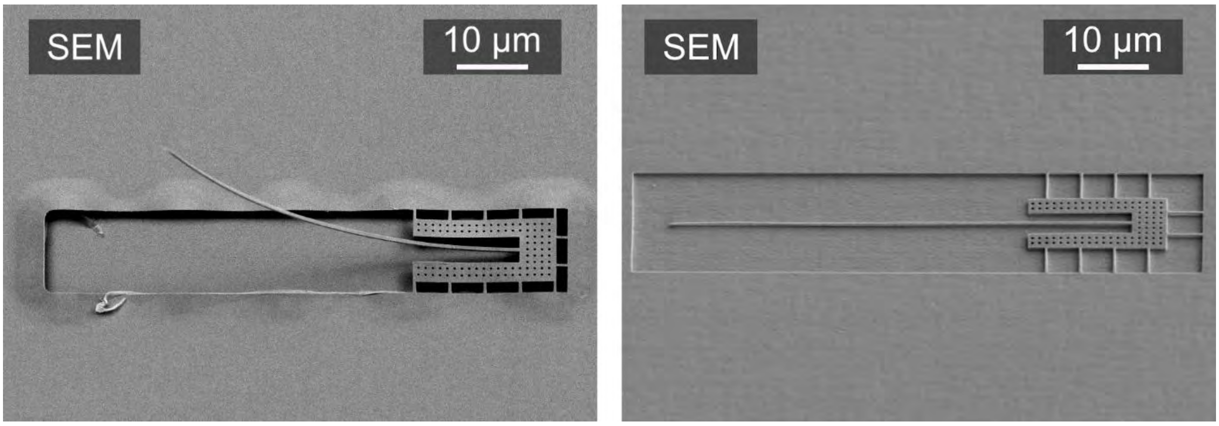

Figure 1: Scanning electron microscope (SEM) images of (left) an underetched structure bending due to strain in the material and (right) a similar structure realized using a different epitaxial growth.

[1] R. Houdré, H. Morkoç: Critical Reviews in Solid State and Material Sciences 16.2, p.91 (1990).

[2] R. Sittig, et al.: Nanophotonics 11.6, p. 1109 (2022).

Scalable Quantum Photonic Platform Based on Site-Controlled Quantum Dots Coupled to Circular Bragg Grating Resonators

Kartik Gaur[1*], Avijit Barua[1], Sarthak Tripathi[1], Leo J. Roche[1], Steffen Wilksen[2], Alexander Steinhoff[2], Sam Baraz[1], Neha Nitin[1], Chirag C. Palekar[1], Aris Koulas-Simos[1], Imad Limame[1], Priyabrata Mudi[1], Sven Rodt[1], Christopher Gies[2], Stephan Reitzenstein[1]

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The realization of large-scale quantum photonic circuits critically relies on the ability to integrate solid-state quantum emitters with nanophotonic structures in a manner that is both deterministic and compatible with scalable fabrication. Among various epitaxial approaches, metal-organic chemical vapor deposition (MOCVD) growth of buried-stressor-based InGaAs site-controlled quantum dots (SCQDs)[1, 2] stands out as a powerful route, combining high material quality with precise strain-driven spatial determinism, and enabling advanced quantum photonic devices such as single-photon sources[3] and microlasers[4].

In this work, we present a fully lithography-compatible, alignment-free integration strategy for embedding MOCVD-grown SCQDs directly into circular Bragg grating (CBG) resonators[5]. The process eliminates conventional localization or feedback steps such as cathodoluminescence (CL) or photoluminescence (PL) mapping, alignment-marker referencing, and in-situ lithography, thereby enabling a room-temperature, wafer-scale fabrication workflow. Finite-element simulations guided the optimization of the cavity geometry and overgrowth design to maximize the photon extraction efficiency (PEE).

Comprehensive characterization of a 6x6 SCQD-CBG device array reveals a remarkable fabrication yield and spatial precision, with 35 devices lying within 20% of the simulated PEE optimum, underscoring the reproducibility of the buried-stressor SCQD growth and pattern transfer. A controlled study across devices with varying radial offsets quantitatively establishes the relationship between emitter displacement and photonic performance, showing that photon extraction, emission linewidth, and single-photon indistinguishability follow the predicted spatial dependence. The best-aligned emitter, offset by only 54 nm from the CBG-mesa's centre, exhibits 47.1(3.8)% PEE, 1.41(22) GHz linewidth, 99.58(18)% single-photon purity, and 89(4)% Hong-Ou-Mandel visibility under quasi-resonant excitation, representing a record performance for any SCQD-based integrated device.

This demonstration highlights how precise MOCVD strain engineering combined with optimized nanophotonic design enables a new class of scalable, high-performance single-photon sources. The approach unites deterministic epitaxial growth with industrially viable fabrication, marking a decisive step toward wafer-level, alignment-free quantum emitter arrays for integrated quantum communication, computation, and photonic neuromorphic architectures.

[1] A. Strittmatter, et. al., Applied Physics Letters, 100(9):093111, 03 2012.
[2] K. Gaur, et. al., Mater. Quantum. Technol. 5 022002 2025.
[3] J. Große, et. al., APL Photonics, 5(9):096107, 09 2020.
[4] A. Kaganskiy, et. al., Optica, 6(4):404–409, 04 2019.
[5] K. Gaur, et. al., In preparation 2025

Capacitance–Voltage Spectroscopy for Characterizing Quantum Dot Electronic Structure and Epitaxial Layer Quality

P. J. Badura,[1,*] N. F. Brosda,[1] D. Kohminaei,[1] G. N. Nguyen,[1] A. R. Korsch,[1]
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Capacitance–voltage (CV) spectroscopy provides a powerful means of probing the electronic structure of quantum dots (QDs) by monitoring the differential capacitance associated with electron tunneling between QD states and a Fermi reservoir. From such measurements, conduction-band energies, tunnel coupling, and addition energies can be extracted [1].

CV spectroscopy has been established as both a quantitative probe and a diagnostic tool for assessing material quality. Overheating a contaminated aluminum effusion cell prior to molecular beam epitaxy (MBE) growth has been shown to effectively remove impurity-related trap states that would otherwise cause broadening, hysteresis, and illumination-induced shifts in the CV spectra of QDs—thereby restoring sharp, reproducible features characteristic of low-noise heterostructures [2].

Recent work has refined the interpretation of ensemble QD CV measurements by identifying frequency- and temperature-dependent peak shifts arising from energy-dependent tunneling, modeled within a master-equation framework. This analysis shows that at low temperatures, energy-level dispersion dominates, while at high temperatures and frequencies, shifts arise from optimized in- and out-tunneling events [3].

Current studies on InAs QDs grown by cyclic gradient growth show consistent correlations between photoluminescence transition energies and CV-derived ground-state energies within each growth cycle, while distinct intergenerational shifts in the ground-state energy reflect systematic variations introduced by the cyclic growth process [4].

[1] H. Drexler, D. Leonard, W. Hansen, J. P. Kotthaus, and P. M. Petroff: *Phys. Rev. Lett.* **73**, 2252 (1994).

[2] G. N. Nguyen, A. R. Korsch, M. Schmidt, C. Ebler, P. A. Labud, R. Schott, P. Lochner, F. Brinks, A. D. Wieck, and A. Ludwig: *J. Cryst. Growth* **550**, 125884 (2020).

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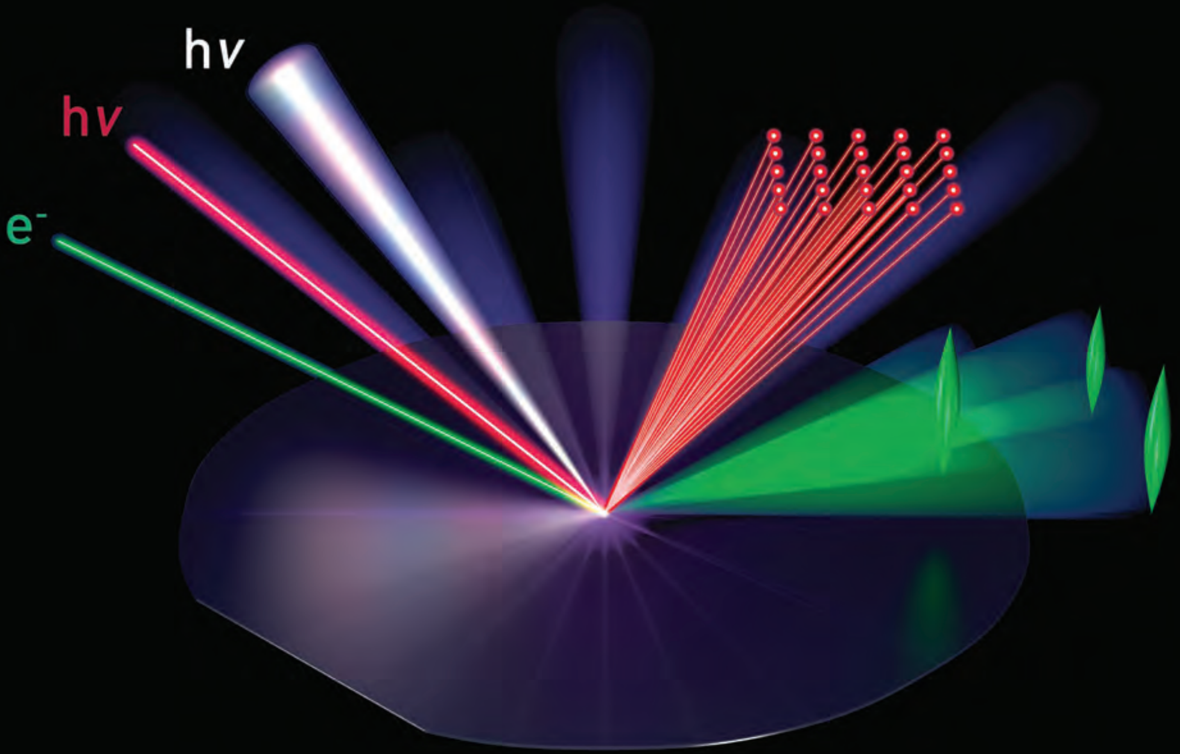

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Wednesday, December 3rd 2025, 13:10 – 14:50

Schinkelsaal

Nitrides: Characterization

13:10-13:30	Kowallik - Determination of optical losses in AlGaN-based multimode waveguides
13:30-13:50	Zameshin - Analytical X-ray Solutions for thin film and wafer analysis
13:50-14:10	Dreyer - Nano-characterization of structural and optical properties of a red-emitting InGaN-LED
14:10-14:30	Grieger - Study of defect transitions by surface photovoltage spectroscopy
14:30-14:50	Ibrahimkutty - High-Resolution XRD Analysis of Compound Semiconductor Materials Using the Rigaku SmartLab Diffractometer

Determination of optical losses in AlGaN-based multimode waveguides

V. Kowallik,[1,*] M. Guttmann,[2] B. Marx,[1] V. König[1], L. Wildenburg[1], T. Wernicke[1] and M. Kneissl[1,2]

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Photonic integrated circuits (PICs) might allow to condense complex optical setups into square millimeter sized chips. PICs in the UV spectral range could enable sensing of gases, biomolecules or chemicals in water by absorption or Raman spectroscopy. UV PICs require wide bandgap materials to ensure UV transparency. 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 in the UVC spectral range below 280 nm. In this work, the absorption in 50 µm, 100 µm and 200 µm wide n-$Al_{0.76}Ga_{0.24}N$ waveguides were investigated using UV-LEDs emitting at 262 nm and detectors of the same heterostructure. The samples were grown on AlN/sapphire templates by metal-organic vapor phase epitaxy (MOVPE). The photocurrent was measured using an integrated AlGaN photodiode and was found to decrease exponentially with increasing waveguide length corresponding to optical losses of (27±3) cm^{-1}. For the loss determination, the reflection from the sapphire backside needs to be considered especially for longer waveguide lengths to avoid underestimation of the optical losses. By Monte-Carlo ray-tracing simulations, we separated the optical losses in (21±3) cm^{-1} propagation losses and (6±1) cm^{-1} scattering losses.

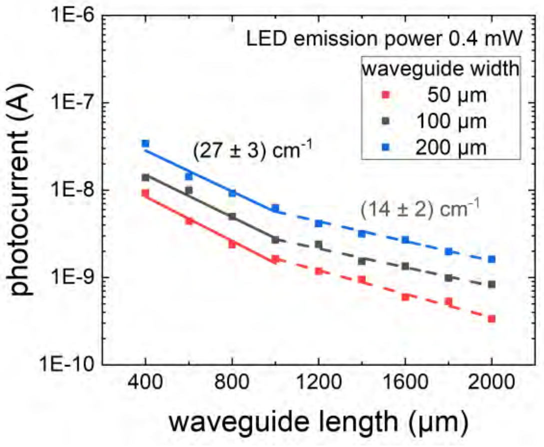

Fig. 1a. Photocurrent measured at AlGaN-based photodiode vs waveguide length for waveguide width of 50 µm, 100 µm and 200 µm

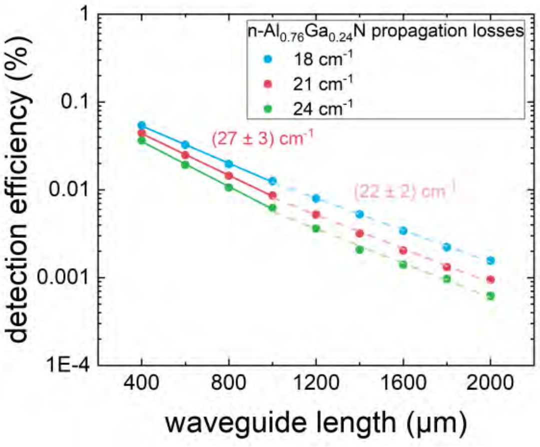

Fig. 1b. Optical losses from ray-tracing simulations for different n-AlGaN propagation losses

Analytical X-ray Solutions for thin film and wafer analysis

A. Zameshin,[1,]* A.Pustovarenko,[1] A. Bharti, K. Gratz
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X-ray diffraction methods are a very important non-destructive tool in analysis of thin films and bulk crystals alike. The ability to accurately measure lattice d-spacing in a variety of geometries provides structural information, not only about lattice parameters, phase identification and crystal orientations, but also about different metrics of crystal and film quality. For thin films, obtainable parameters include composition, relaxation, micro-strain, stress, mosaicity, lateral and vertical correlation lengths and crystallite size, microscopic tilts and twists, dislocation density; as well as layer thickness, roughness / diffuseness, and density. For bulk crystals, X-ray diffraction can be used to determine crystal quality via rocking curves, and crystal orientation, for example the offcut magnitude and direction.

In this talk, we present the capabilities of a few different laboratory diffractometers. We demonstrate several ways in which Reciprocal Space Mapping (RSM) can be performed, such as coplanar Ultrafast RSM using area detector or non-coplanar RSMs from fiber textured films. We compare several in-plane geometries on Empyrean and on X'Pert^3 MRD (XL). We demonstrate the benefits of using a rotating slit in combination with an X-ray lens for consistent sample illumination at any Chi tilts, improving the quality of texture, non-coplanar RSM, and in-plane measurements.

Next, we focus on the ability to make the analysis of X-ray reflectivity semi-model-independent, by using our patented free-form analysis method. This can be especially useful in research process in cases when the layer model is difficult to build - either because of unspecified surface oxidation, interlayer formation, density gradients, or any other processes that would need to be explicitly known in advance to be included in a model.

Finally, we present work on the rapid orientation determination of bulk crystals (wafers).

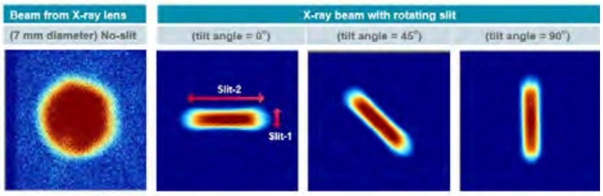

Fig. 1. Effect of rotating slit on a direct beam shape

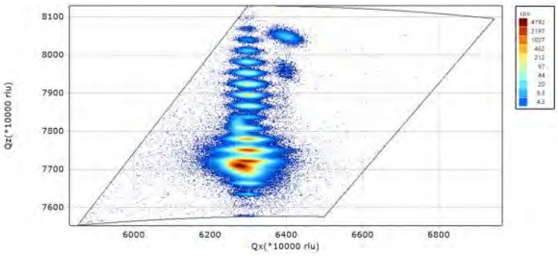

Fig. 2. Fast RSM of GaN HEMT structure

Nano-characterization of structural and optical properties of a red-emitting InGaN-LED

N. Dreyer,[1,*] F. Bertram,[1] G. Schmidt,[1] J. Christen,[1] Z. Chen,[2] and X. Wang[2]
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In this study, a red-emitting InGaN-LED has been investigated by cathodoluminescence spectroscopy performed in a scanning transmission electron microscope (STEM-CL). The LED structure was grown by MOVPE on a sapphire substrate with an undoped GaN buffer layer followed by a GaN:Si layer ($n \quad = 2*10^{19}$ cm^{-3}) each with a thickness of 1.8 µm. The active region consists of a stack of three identical regions. Every region consists of two $In_{0.15}Ga_{0.85}N$/GaN QWs emitting in the blue spectral range (BQW) and a single red emitting QW (RQW) with [In] = 40 %. Each sequence is completed by a 1 nm thick $Al_{0.32}Ga_{0.68}N$ confinement layer. On top, the p-doped region with a p-$Al_{0.17}Ga_{0.83}N$ electron blocking layer (EBL), a p-GaN layer ($p = 1.6*10^{17}$ cm^{-3}) and a p^+-GaN cap follows. For light out-coupling through the substrate a dielectric distributed Bragg reflector (DBR) was deposited on top.

The fully processed, diced and contacted mini-LED device was operated under electrical injection at room temperature. The electroluminescence spectrum is dominated by a broad red emission with a peak wavelength of λ = 644 nm. In addition, a green luminescence band with an intensity one order of magnitude weaker is observed around 540 nm. Notably, no significant shift of the peak position was observed under varying injection current densities.

STEM-CL measurements of the sample in cross section allow the characterization of each individual layer. The luminescence (at T = 17 K) of the GaN buffer is dominated by excitonic emission (D^0,X) at 357.0 nm (3.472 eV). The observed broader near band edge emission in the n-doped GaN region obtained at higher energy is attributed to band-band recombination: under consideration of band gap renormalization and conduction band filling (Burstein-Moss effect), the line shape analysis yields a charge carrier density of $n = 6*10^{18}$ cm^{-3} here.

In the active region, the emission of the BQWs and RQWs (λ_{BQW} = 400 nm, λ_{RQW} = 577 nm) exhibit a systematic shift to longer wavelengths in growth direction. For the BQWs, a peak wavelength shift of 80 meV is obtained. The influence of indium incorporation, strain as well as QW thickness variations will be discussed. Highly spectrally resolved CL analysis of the 1st BQW reveals a superposition of sharp emission lines with FWHM down to 5 meV indicating a dot-like behavior. The RQW emission can be correlated to each individual well within the three stacks. The FWHM of the RQW luminescence is 172 meV. This broad emission is caused by lateral variations within the active region. In particular at extended defect, the RQW emission shifts to lower energies by 365 meV. The homogeneity of the RQW emission will be addressed. The vertical and lateral capture process of excess carriers will be discussed in detail.

Study of defect transitions by surface photovoltage spectroscopy

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[2] Leibniz-Institut für Kristallzüchtung, Max-Born-Str. 2, 12489 Berlin, Germany
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AlN and Ga_2O_3 are emerging semiconductors for power electronics applications. Their material development is ongoing and their elevated bandgaps makes optical metrology challenging. Surface photovoltage spectroscopy (SPV) allows for the detection of electronic defect transitions in semiconductors without the need for contact preparation, i.e. defect transitions can be characterized at different stages of technology. The study of defects in ultra-wide bandgap semiconductors by SPV techniques requires the continuous variation of photon energies from the near infrared to the deep ultra-violet which is made possible by a new monochromator design (DPM100, Freiberg Instruments). In this work we present a method to calculate the effective absorption cross section (Figure 1) of semiconductor materials by surface photovoltage spectroscopy. We compare different material growth methods and highlight opportunities and challenges of this metrology method looking at first processing results.

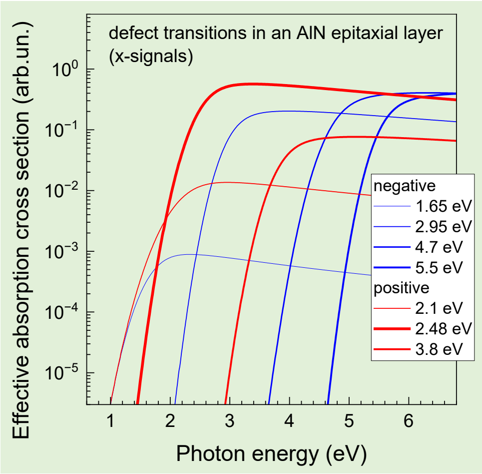

Figure 1 Defect cross section of an AlN epitaxial layer on Sapphire grown by sputter epitaxy and subsequent annealing.

High-Resolution XRD Analysis of Compound Semiconductor Materials Using the Rigaku SmartLab Diffractometer

S. Ibrahimkutty,[1,*]
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For the fabrication of microelectronic and optoelectronics devices the crystalline quality of semiconductor layers is a key factor. High resolution X-ray diffraction is a versatile and powerful tool for the characterization of compound semiconductor materials and devices. Quick and non-destructive characterization of thickness, composition, quality, orientation, lattice strain, etc. are feasible by X-ray diffraction measurements.

This presentation will cover different XRD based approaches, the basic and sophisticated characterization of epitaxial layers by means of a Rigaku SmartLab diffractometer [1]. The thickness and composition of epitaxially grown layers are evaluated from high resolution 2theta-omega scans (Figure 1). The selection of optical components for high resolution measurements will be discussed. Various measurement geometries of SmartLab using its 5 + 1 circle goniometer will be discussed.
Rocking curve measurements can be used for the determination of crystal quality, curvature, and offset angles of semiconductor layers [2]. Further, the possibility to extract the correct in-plane and out of plane lattice parameter and strain involved in the system by appropriate reciprocal space map (RSM) measurements will be shown (Figure 2).

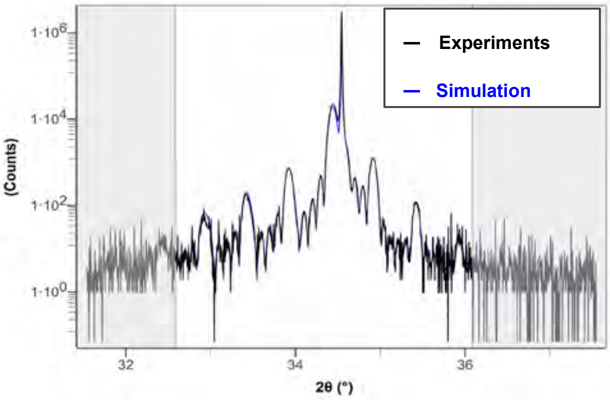

Fig 1: High resolution 2theta-Omega scan of GaN/InGaN MQW Super lattice.

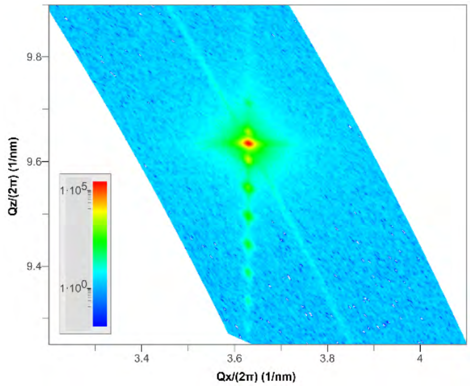

Fig 2: RSM measured at asymmetric (01-15) peak of GaN/InGaN MQW super-lattice.

[1] T. Konya, The Rigaku Journal 25 -2 (2009).
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Gartensaal

15:50-16:30	**Invited: Eickhoff - Molecular beam epitaxy of group III-sesquioxides: What's so special?**

Arsenide & Phosphide based QDs and NWs

16:30-16:50	Reuter - Droplet etched quantum dots in the InP/$In_yAl_{1-y}As/In_xGa_{1-x}As$ system for single photon emission in the optical C-band
16:50-17:10	Anderson - Generation Waves: Exploring Spatial Modulations of InAs QDs' Structure and Properties for Telecom O-Band Applications
17:10-17:30	Sauer - Etching of Nanoholes for the Growth of site-controlled InAs Qds in the telecom C-band
17:30-17:50	Bohlemann - Towards stable passivation layers on III-V-semiconductor nanowires for photoelectrochemical water splitting applications

Molecular beam epitaxy of group III-sesquioxides: What's so special?

A. Karg,[1] M. S. Williams,[1] S. Raghuvansy,[1] M. Alonso-Orts,[1,2] M. Schowalter,[1]
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[1]Institute of Solid State Physics, University of Bremen, Bremen, Germany
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The growth of group III-sesquioxides, namely of the $(Al,In,Ga)_2O_3$ material system, has attracted increasing interest during the last decade. Molecular beam epitaxy (MBE) of Ga_2O_3-based materials has been shown to be confronted with specific difficulties which mainly originate in the formation of the volatile suboxide Ga_2O its subsequent desorption in Ga-rich growth conditions, ruling out growth in the adsorption-controlled regime when elemental Ga is used as a source material. This behavior is in strong contrast to MBE-growth of established group III-based compound semiconductors such as GaN or GaAs.

Different routes to overcome these problems by actively changing the chemistry on the growth surface have been proposed. The addition of Sn or In as additives during the growth process does not only significantly widen the accessible growth window to the Ga-rich regime but at the same time to leads to a strong enhancement of the growth rate [1,2], hence, these approaches are generally addressed as "catalyzed" (CatMBE). However, the microscopic mechanism of the latter effect and other details of the CatMBE process, e.g. the role of the additive on the oxygen-supply on the growth surface, the occurrence of a phase-transition from β- to κ-Ga_2O_3, the incorporation of the respective additive into the host lattice or its role as a surfacvtant [3], are still not understood in detail. In a second approach, the formation of the volatile sub-oxide Ga_2O as the first step in a two-step growth process [4] is suppressed by direct supply of the suboxide Ga_2O rather than elemental Ga as the metal source during MBE growth. This technique, called suboxide-MBE (S-MBE) leads to very high growth rates at comparatively low substrate temperatures, smooth surfaces, high quality interfaces of the substrate [5]. S-MBE is also considered as powerful technique to control the incorporation of dopants into the material [6].

In this contribution we give an overview of recent results in MBE growth of Ga_2O_3-related materials and heterostructures using CatMBE and S-MBE. We discuss experimental findings and details of these novel growth techniques as well as open questions that need to be further addressed both in theory and experiment.

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[6] K. Azizie et al., APL Mater. **11**, 041102 (2023)

Droplet etched quantum dots in the InP/In$_y$Al$_{1-y}$As/In$_x$Ga$_{1-x}$As system for single photon emission in the optical C-band

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GaAs/Al$_x$Ga$_{1-x}$As quantum dots (QDs) fabricated via local droplet etching (LDE) have been proven to be the current gold standard for generating polarization entangled photon pairs, as they exhibit very low fine-structure splitting (fss) due to good in-plane symmetry and their negligible strain [1]. However, for the GaAs/Al$_x$Ga$_{1-x}$As system one is limited to photon emission around 780 nm. In this contribution, we present the adaptation of the LDE technique to the InP/In$_y$Al$_{1-y}$As/In$_x$Ga$_{1-x}$As system for photon emission in the optical C-band. We show that under optimized process parameters for the etching process we can produce nanoholes that display very good symmetry when measured with atomic force microscopy (AFM). We will discuss the influence of the etching material (In, Al, InAl), the etching temperature and the amount on etching material on the resulting nanohole geometry. Etching temperatures of 410 °C and 435 °C are optimum regarding hole depth and in-plane symmetry. Our experiments further show that these nanoholes can be filled with In$_x$Ga$_{1-x}$As and that the filling works better when utilizing an As$_4$ environment instead of As$_2$. Finally, we demonstrate that the filled nanoholes emit light in the optical C-band when embedded in an In$_{0.52}$Al$_{0.48}$As matrix. µ-photoluminescence spectroscopy reveals sharp emission lines typical for semiconductor QDs.

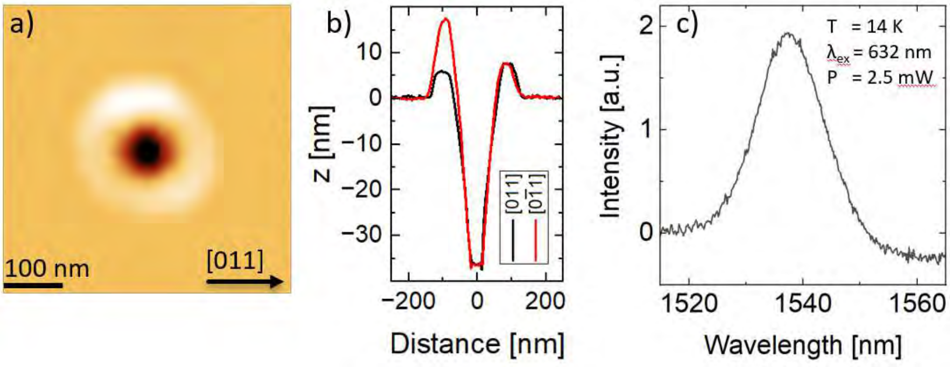

Figure 1: a) Exemplary AFM image of a nanohole etched into an In$_{0.52}$Al$_{0.48}$As layer by depositing InAl droplets. b) Corresponding line scans in the two main crystalline directions. c) Ensemble photoluminescence signal from In$_{0.56}$Ga$_{0.44}$As QDs embedded in an In$_{0.52}$Al$_{0.48}$As matrix, grown by filling nanoholes produced with the same parameters as in a) and overgrown with In$_{0.52}$Al$_{0.48}$As.

References

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Generation Waves: Exploring Spatial Modulations of InAs QDs' Structure and Properties for Telecom O-Band Applications

L. Anderson,[1,*] D. Kohminaei,[1,2] M. Schmidt,[1] S. Krüger,[1] N. Spitzer,[1] and A. Ludwig [1]
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[2] University of Vienna, Faculty of Physics, Vienna, Austria
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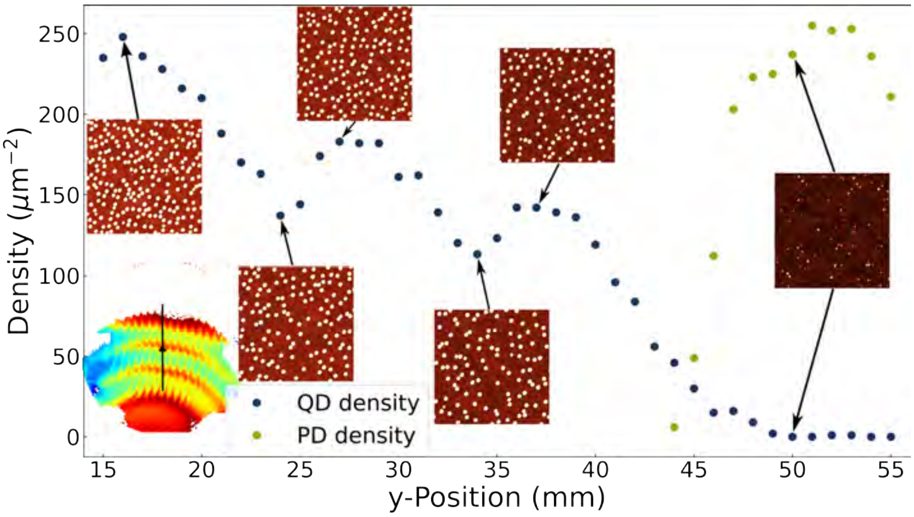
InAs quantum dots (QDs) emitting at approximately 1.3 micrometers were successfully fabricated using the Stranski-Krastanov growth mode combined with a strain reduction layer. This emission wavelength is particularly advantageous for applications of the QDs as high-quality, deterministic single-photon emitters with low fiber loss in telecom systems. To optimize these properties, we controlled the emission wavelength and QD density through a gradient growth technique. In this study, we employed a cyclic gradient growth technique, revealing periodic modulations in QD density, structural quantities, and thus the emission wavelength, driven by nucleation waves, i.e. a new generation of QDs is formed each time a critical material amount for nucleation is reached. We explore the correlations between the structural characteristics and opto-electronic properties by atomic force microscopy (AFM) and photoluminescence (PL) as well as capacitance-voltage spectroscopy. Analyzing the QDs' spatial distribution along the generation waves gives further insights into how growth conditions drive spatial regularity and optical homogeneity. We discuss the intricate correlations among the QDs' properties, identifying optimal regions for density and emission wavelength across our 3-inch wafers, and propose a modified deposition scheme to enhance the usable area of the wafers.



Density of QDs and predots (PDs) along the In gradient. QD's density, size, and emission wavelength oscillate with the generation waves, as indicated also by the inserted AFM images and PL map. When the critical In layer thickness is undershot, no mature QDs nucleate anymore, but only PDs.

Etching of Nanoholes for the Growth of site-controlled InAs QDs in the telecom C-band

M. Sauer,[1,]* L. Hoxha,[1] A. Keyath,[1] M. Emmerling[1], S. Krüger[1], S. Höfling[1] and A. Pfenning[1]
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The growth of deterministically placed semiconductor quantum dots (QDs) are essential for realizing scalable quantum photonic technologies [1]. We address this challenge by developing a molecular beam epitaxy (MBE) growth for prepositioned InAs QDs on InP substrates, where nanohole arrays enable deterministic site control. Electron-beam lithography is employed to define the pattern, followed by a wet chemical etch to create nanoholes with controlled depth and lateral dimensions (see Fig. 1). This approach offers a straightforward and highly selective method for preparing ordered nucleation sites [2], while minimizing surface damage.

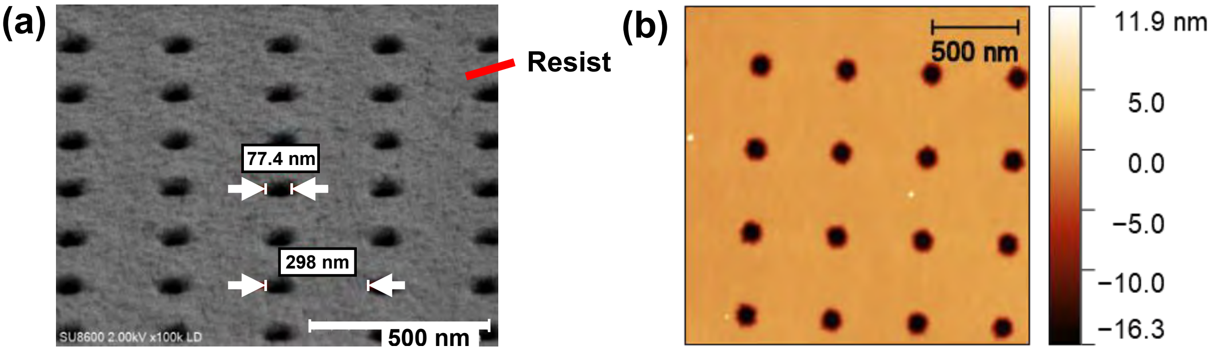

Figure 1. (a) Scanning Electron Microscopy (SEM) image of nanohole arrays after e-beam lithography. (b) Atomic-Force Microscopy (AFM) image of nanoholes after wet-chemical etching.

Nanoholes act as preferential nucleation centers during MBE growth, locally modifying the surface energy landscape and confining adatom diffusion [3]. By optimizing the InAs deposition parameters—substrate temperature, beam flux ratios, and nominal coverage—selective QD nucleation within the etched nanoholes is targeted, while suppressing random island formation.

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Towards stable passivation layers on III-V- semiconductor nanowires for photoelectrochemical water splitting applications

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The production of green hydrogen and renewable electricity is expected to be crucial for the transition to a sustainable and climate-neutral economy. III-V semiconductors are promising materials for this purpose, as they offer record efficiencies in both photovoltaics [1] and photoelectrochemical (PEC) water splitting [2]. However, their large-scale implementation remains a challenge due to the material criticality of, for example, In, Ga or As [3,4]. The reduction or substitution of these scarce materials is therefore essential to enable sustainable device concepts. In this context, III–V nanowires (NWs) represent a promising approach. They reduce material consumption compared to planar thin films and show enhanced optical absorption [4], especially when used in NW arrays that can be easily fabricated on a large scale [5]. Their high surface-to-volume ratio is particularly beneficial for solar-to-hydrogen conversion technologies.

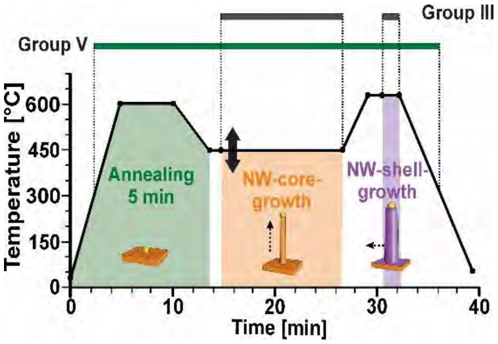

Fig.1: Growth diagram for GaAsP/GaP(N) core shell NWs

However, the intrinsic instability of III-V materials in aqueous electrolytes often leads to rapid corrosion and limited operational lifetimes of photoelectrodes for representative active areas - a challenge that also applies to NW-based systems [4]. To address this limitation, we investigated the growth behavior, electrical characteristics, and corrosion stability of GaAsP NW grown by metal–organic vapor-phase epitaxy (MOVPE) and subsequently passivated with GaP(N) shells. scanning electron microscopy was employed to analyze growth quality, crystal orientation, and defect structures in both GaAsP cores and GaP(N) shells, as well as the degradation behavior before and after multiple hours of water-splitting operation. Our findings reveal that the application of a GaP(N) passivation layer substantially improves the structural integrity and durability of the NW during PEC water splitting application under continuous illumination [3], highlighting a potential pathway toward stable and efficient III-V NW-based PEC photoelectrodes.

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Reactor Type	Face Up / Horizontal
Heating System	2 Zone Resistance Heater
★ Option	Low Vapor Pressure Precursor Supply

Enabling the Future of Gallium Oxide (Ga_2O_3) Semiconductors

Model

FR2000-OX / R&D

Application	Power devices, UV photodetectors
Wafer Size	2”×1
Reactor Type	Face Down / Horizontal
Heating System	3 Zone, Hot-wall System

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MOCVD website

Videos (YouTube)

Wednesday, December 3rd 2025, 16:30 – 17:50

Schinkelsaal

Other Materials

16:30-16:50	Zittel - Chemical Vapor Deposition of Copper Iodide
16:50-17:10	Malindretos - Molecular Beam Epitaxy of 2H-TaS_2 few-layers on GaN(0001)
17:10-17:30	Karg - Growth of rutile GeO_2 by plasma-assisted suboxide molecular beam epitaxy
17:30-17:50	Hoffmann - In-Situ monitoring of metal-induced redox reactions on $SrTiO_3$ by laser reflectometry and x-ray photoelectron spectroscopy

Chemical Vapor Deposition of Copper Iodide

Valeria Zittel[1,*], Stefan Merker[1], Susanne Selle[2], Marius Grundmann[3], and Harald Krautscheid[1]
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[2] Fraunhofer Institute for Microstructure of Materials and Systems IMWS, Walter-Hülse-Straße 1, 06120 Halle, Germany
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Semiconductors are indispensable in electronic devices so that the development of new semiconducting materials and the improvement of their electrical properties are of great interest. The γ-phase of copper(I) iodide is one of the most promising transparent p-type semiconductors because of properties such as a direct band gap (3.1 eV), high hole mobility (44 cm² V^{-1} s^{-1}) and transparency for the visible light (80–90 %) [1]. CuI can be deposited by various methods, e.g., pulsed laser deposition (PLD) [1], iodization of copper films (Bädeker route) [2], or chemical vapor deposition (CVD) [3]. We deposited CuI by CVD on transparent c-plane sapphire substrates using $[Cu(^{s}Bu\text{-}Me\text{-}amd)]_2$ and ^{t}BuI as precursors.

Experiments from earlier studies of our group showed that CVD of CuI on c-sapphire resulted in island growth [3]. Therefore, an alternative approach was investigated. CVD experiments were performed on an epitaxial-grown PLD CuI buffer layer using different deposition conditions. In addition, metallic copper was deposited at different temperatures and subsequently iodized in iodine vapor to yield copper iodide thin films (Bädeker route). The CuI samples were characterized by X-ray diffraction (XRD), optical and electron microscopy.

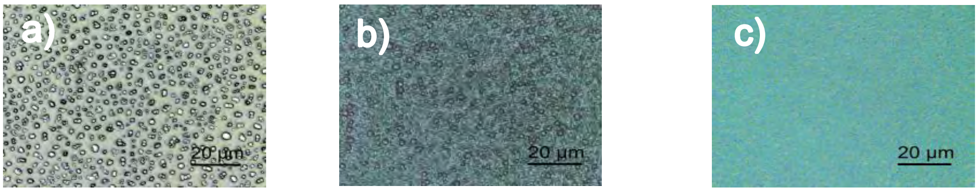

Fig. 1: Laser scanning microscopy: CuI deposition by a) CVD on a PLD CuI buffer layer (CuI islands), b) Bädeker route: Cu deposition at 310 °C and iodization at room temperature (CuI layer), c) Bädeker route: Cu deposition at 210 °C and iodization at room temperature (CuI layer).

[1] P. Storm, M. S. Bar, G. Benndorf, S. Selle, C. Yang, H. von Wenckstern, M. Grundmann, and M. Lorenz: APL Materials 8, 0911151 (2020).

[2] K. Bädeker: Annalen der Physik 327, 749 (1907).

[3] S. J. Merker, V. Zittel, G. Benndorf, M. Grundmann, and H. Krautscheid: Journal of Crystal Growth 663, 128179 (2025).

Molecular Beam Epitaxy of 2H-TaS$_2$ few-layers on GaN(0001)

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Trigonal prismatic tantalum disulfide (H-TaS$_2$) exhibits in the bulk of its 2H polytype a nearly commensurate 3 x 3 charge density wave (CDW) transition below 75 K and a superconducting transition with $T_c = 1$ K. As for other layered transition metal dichalcogenides (TMDs), the electronic properties of 2H-TaS$_2$ are dependent on the layer thickness and can be modified by the underlying substrate.

2H-TaS$_2$ few layers have been grown epitaxially onto GaN(0001). A high substrate growth temperature of 825 ºC induces best structural properties of the overlayer, as revealed by *in-situ* electron diffraction (RHEED and LEED). The 2D-overlayer grows unstrained right after deposition of a monolayer. However, evidence of pits at the interface is provided by scanning transmission electron microscopy, most probably due to GaN thermal decomposition at the high growth temperature. *In-situ* x-ray photoemission spectroscopy shows core level shifts that are consistently related to electron transfer from the n-GaN(0001) to the 2H-TaS$_2$ epitaxial layer as well as the formation of a high concentration of nitrogen vacancies close to the interface. Further, no chemical reaction at the interface between the substrate and the grown TaS$_2$ overlayer is deduced from XPS, which corroborates the possibility of integration of 2D 2H-TaS$_2$ with an important 3D semiconducting material like GaN.

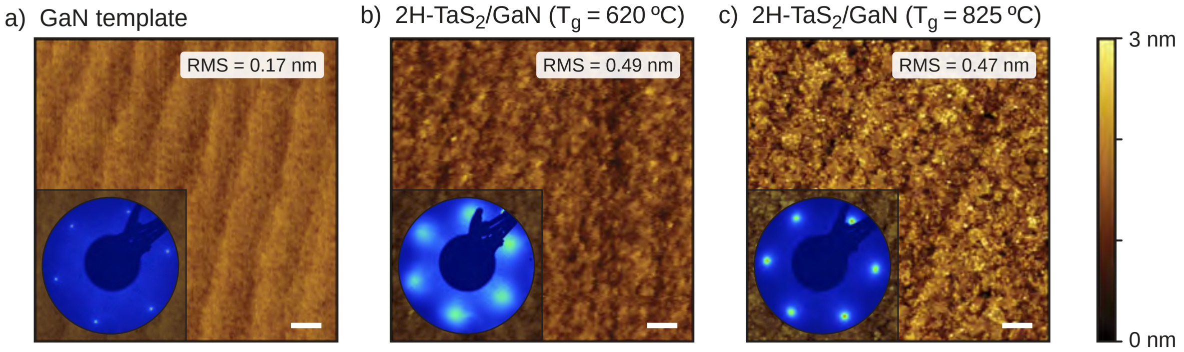

Figure 1: AFM topography measurements (1 µm × 1 µm) of (a) the GaN substrate, (b) after growth of 2H-TaS$_2$ (6 ML) at T_g = 620 °C and (c) after growth at T_g = 825 °C. The scale bar length is 100 nm. Corresponding LEED patterns measured at a beam energy of 100 eV are reported in the insets. The slight rotation of the LEED pattern in (c) is due to a rotation of the sample holder.

[1] C. Hilbrunner, T. Meyer, J. Malindretos and A. Rizzi: 2D Mater. **12**, 045027 (2025), doi: 10.1088/2053-1583/ae1516.

Growth of rutile GeO_2 by plasma-assisted suboxide molecular beam epitaxy

A. Karg,[1,*] S. Phiw-Ondee,[1] M. Alonso-Orts,[1,2] M. Schowalter,[1]
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[1]Institute of Solid State Physics, University of Bremen, Bremen, Germany
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Rutile germanium dioxide (r-GeO_2) is an emerging candidate among ultra-wide bandgap (UWBG) semiconductors, possessing a bandgap of approximately 4.6 eV [1]. Such materials are crucial for modern technologies, in particular for their application in high-power electronic devices. Compared to another emerging UWBG oxide semiconductor β-Ga_2O_3 (4.85 eV [1]), r-GeO_2 has a significantly larger thermal conductivity, 11-27 W/mK for β-Ga_2O_3 [1] and 51 W/mK for r-GeO_2 [1]. This superior property makes r-GeO_2 more suitable for the next generation of devices. Furthermore, while Ga_2O_3 can only be doped n-type, both n- and p-type conductivity are predicted for r-GeO_2 [2], a very rare but desirable property of UWBG semiconductors.

Regarding the epitaxial growth of r-GeO_2, only a limited number of reports exist, for instance by MOCVD [3], PLD [4] and sputtering [5]. In case of MBE, there is only a single report on crystalline r-GeO_2 growth by ozone-assisted MBE [6] on graded buffer r-plane Al_2O_3 substrates, indicating a very narrow growth window.

This work demonstrates the growth of r-GeO_2 on m-plane Al_2O_3 substrates by plasma-assisted MBE using a Ge-suboxide source. Sn was supplied from a metallic Sn source. The layer structure consists of the initially grown buffer layer of SnO_2, followed by $Ge_xSn_{1-x}O_2$ layers with various compositions. Subsequent nucleation and growth of pure r-GeO_2 on such templates is achieved by a specific surface pre-treatment consisting of etching and Ge-enrichment. The suboxide nature of the Ge-source is confirmed by the adsorption-controlled growth of GeO_2. All $Ge_xSn_{1-x}O_2$/GeO_2 layers are characterized by X-ray diffraction (XRD) and atomic force microscopy (AFM), selected samples were analyzed by scanning transmission electron microscopy (STEM).

[1] M. Labed et al., Materials Today 83, 513-537 (2025)
[2] S. Chae et al., Appl. Phys. Lett. 114, 102104 (2019)
[3] I. Rahaman et al., Appl. Phys. Lett. 125, 102103 (2024)
[4] G. Deng et al., Appl. Phys. Lett. 119, 182101 (2021)
[5] C. Wei et al., Vacuum 225, 113233 (2024)
[6] S. Chae et al., Appl. Phys. Lett. 117, 072105 (2020)

In-Situ monitoring of metal-induced redox reactions on $SrTiO_3$ by laser reflectometry and x-ray photoelectron spectroscopy

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Strontium titanate ($SrTiO_3$) has been the workhorse for emergent phenomena in perovskite oxides for decades, hosting many fundamental physics phenomena ranging from quantum paraelectricity to superconductivity. In particular, when interfaced with other materials, $SrTiO_3$ gives rise to novel phenomena beyond its intrinsic bulk properties, such as the formation of two-dimensional electron gases (2DEGs) [1]. Recently, increasing attention has been brought to 2DEGs that emerge from redox reactions induced by amorphous metal deposition on $SrTiO_3$ surfaces [2]. However, the investigation of such redox processes typically requires elaborate experimental setups, such as in-situ photoelectron spectroscopy, and involves long measurement cycles.

Here, we introduce laser reflectometry (LR) as a complementary technique that enables monitoring of redox reactions at oxide/metal interfaces (Fig. 1a). We focus on the well-studied $SrTiO_3/AlO_x$ system to elucidate redox reactions and benchmark our LR results. We show that LR in an oxide molecular beam epitaxy setup can distinguish between Al deposition on non-reacting $DyScO_3$ substrates (upper inset in Fig. 1a) and Al oxidation, e.g. through oxygen scavenging from $SrTiO_3$ (lower inset in Fig. 1a). Atomic force microscopy, x-ray photo-electron spectroscopy (XPS) (Fig. 1b), van der Pauw, and Capacitance-Voltage measurements corroborate our findings. Our results demonstrate how LR can deepen the understanding of redox processes at oxide/metal interfaces and guide future investigations.

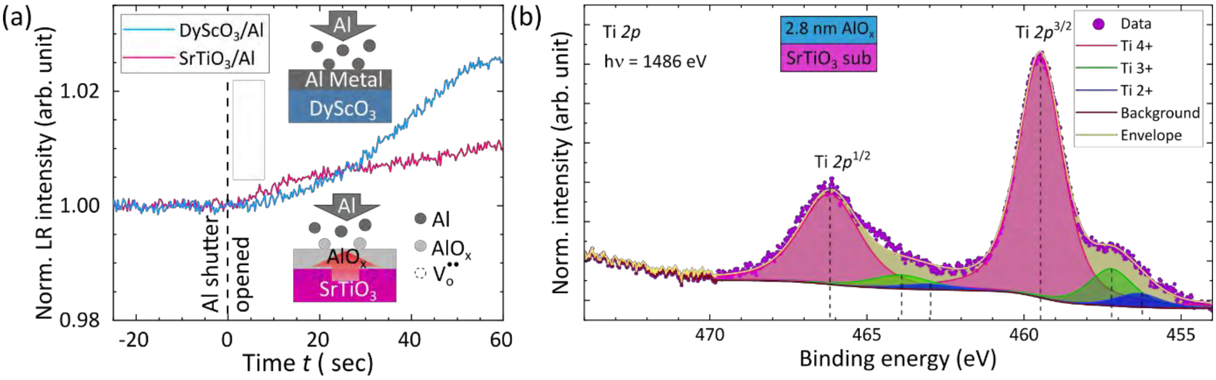

Fig. 1. a) LR intensity during Al deposition on inert $DyScO_3$ (blue) and reactive $SrTiO_3$ (magenta) substrates. b) XPS spectra of the Ti*2p* core levels. The presence of Ti^{3+} and Ti^{2+} states at lower binding energies indicate the presence of a 2DEG formed by oxygen vacancies at the interface.

[1] A. Ohtomo, and H. Y. Hwang., Nature 427, 423 (2004).

[2] T. Rödel, *et al.,* Adv. Mater. 28, 1976 (2016).

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Thursday, December 4th 2025, 9:00 – 10:40

Gartensaal

9:00-9:40	**Invited: Semond - Molecular Beam Epitaxy of Niobium Nitride III-N/NbN Hybrid Heterostructures**

Nitrides: Preparation

9:40-10:00	Bilke - Towards a clean GaN/GaN regrowth interface
10:00-10:20	Brunner - GaN-on-GaN interface optimization for III-Nitride electronic device structures
10:20-10:40	Kreuzer - High-Temperature Annealing of AlN as Template for UV LEDs and Power Electronics in CO and NH3 Containing Atmospheres

Molecular Beam Epitaxy of Niobium Nitride: III-N/NbN Hybrid Heterostructures

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Niobium Nitride (NbN) is an interesting superconducting material for quantum technologies [1]. However, NbN is a relatively complex material [2]. NbN is mostly produced by sputtering techniques [3]. In recent years, several studies have demonstrated epitaxial growth of NbN and the possibility to combine NbN with III-N semiconductor materials [4-7]. Using ammonia-assisted molecular beam epitaxy (NH_3-MBE), this work present a study of the epitaxy of NbN and the epitaxial growth of hybrid III-N/NbN heterostructures.

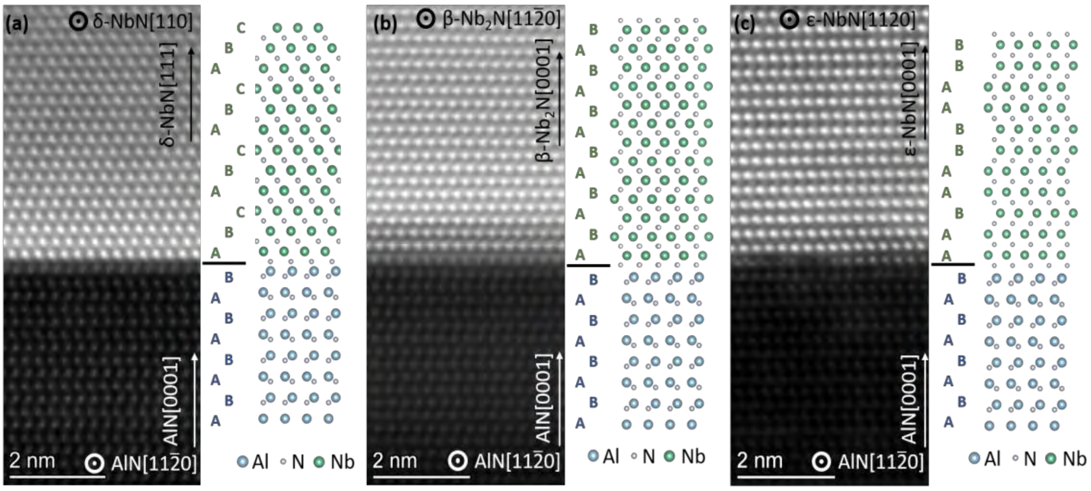

Figure: HAADF-STEM images of three different NbN/AlN heterostructures.

This work is first dedicated to epitaxy of NbN on AlN-on-Silicon thin films, focusing on the different NbN phases, the characterization of their properties, and the quality of the interfaces. This study demonstrates that NH_3-MBE allows for the in-situ monitoring of cubic-hexagonal phase transitions as well as stoichiometric modifications, illustrating the complexity of NbN thin film growth. Then, several III-N/NbN epitaxial heterostructures are presented and discussed highligting the potential of this material system for the epitaxial growth of complex hybrid semiconductor/metal/superconductor heterostructures.

[1] S. Kim *et al.* : Commun Mater 2, 98 (2021)
[2] F. Mercier *et al.* : Surface & Coatings Technology 260,126 (2014)
[3] R. Schneider *et al.* : Cryst. Res. Technol. 44, No. 10, 1115 (2009)
[4] S. Katzer *et al.* : Phys. Status Solidi A, 217,1900675 (2020)
[5] P. Dang *et al.* : Science Advances Vol 7, Issue 8 (2021)
[6] R. Cheng *et al.*: Appl. Phys. Lett. 117, 132601 (2020)
[7] A. Iovan *et al.* : Appl. Phys. Lett. 123, 252602 (2023)

Towards a clean GaN/GaN regrowth interface

M.-L. Bilke,[1,*] A. Großer,[1] J. Gärtner,[1] A. Ruf,[1] T. Mikolajick,[1,2] and S. Schmult,[2]
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[2] TU Dresden, Institute of Semiconductors and Microsystems, 01187 Dresden, Germany
[*] Corresponding author: Marie-Louise Bilke (Marie-Louise.Bilke@namlab.com)

A parasitic, conductive channel at the substrate/regrowth interface in GaN/AlGaN heterostructures grown on GaN substrates deteriorates the transfer characteristics of lateral field-effect transistors, as these devices suffer from leakage in their off-state after depletion of the 2DEG formed at the GaN/AlGaN interface. The origin of the parasitic channel is silicon contamination from the atmosphere on the substrate surface.[1] Various ex-situ cleaning procedures did not yield a significant reduction of the Si contamination at the regrowth interface. A potential solution is the formation of a passivation layer that can be desorbed in-situ prior to growth in MBE or MOVPE. GaAs research showed that surface oxide could be desorbed in MBE environment prior to overgrowth.[2] Therefore, an oxidation method should also be developed for GaN, followed by desorption and growth processes by MBE or MOVPE.

A wet chemical oxidation of GaN at different temperatures, with and without UV irradiation, and using different oxidizing agents, was not successful. Both thermal and oxygen-plasma–assisted oxidation produced gallium oxide layers. The oxide desorption in MBE environment prior to overgrowth was incomplete, resulting in deteriorated crystalline quality and surface morphology compared to growth on untreated GaN. It was found, that under the harsh oxygen-plasma and thermal conditions crystalline phases of gallium oxide were formed, which are fairly stable in contrast to the amorphous oxide on GaAs surfaces.

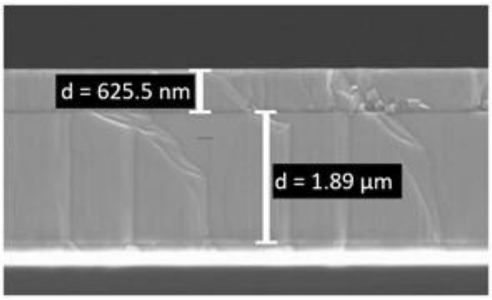

Figure 1: SEM cross-sectional image of the oxidized GaN substrate after oxide desorption and consecutive regrowth of the a GaN/AlGaN stack in MBE invornment.

[1] Schmult, S.; Wirth, S.; Silva, C.; Appelt, P.; Großer, A.; Mikolajick, T. Systematic Suppression of Parasitic Conductivity Highlights Undistorted Quantum Transport in GaN/AlGaN 2DEGs. *J. Cryst. Growth* **2022**, *589*, 126673. https://doi.org/10.1016/j.jcrysgro.2022.126673.

[2] Guillén-Cervantes, A.; Rivera-Alvarez, Z.; López-López, M.; López-Luna, E.; Hernández-Calderón, I. GaAs Surface Oxide Desorption by Annealing in Ultra High Vacuum. *Thin Solid Films* **2000**, *373* (1–2), 159–163. https://doi.org/10.1016/S0040-6090(00)01126-3.

GaN-on-GaN interface optimization for III-Nitride electronic device structures

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Epitaxial growth of GaN layers on native GaN substrates is needed for vertical and lateral electronic device structures with low-defect density. The presence of impurities at the surface of GaN substrates may introduce interface charges and defects that can impair device operation [1]. Recent studies using both in-situ or ex-situ cleaning techniques have shown the difficulties in removing interfacial contaminations [2]. In this work the unintentional incorporation of Si at the regrowth interface is investigated for different substrate storage conditions and pretreatments using secondary ion mass spectrometry (SIMS). Electrochemical capacitance-voltage (ECV) measurements were used to track interface charges. Both wet chemical substrate preparation and in-situ etching with XeF_2 in the MOVPE chamber were investigated. Si contamination could be reduced by more than 95% eliminating any unintentional interface conductivity. Etching conditions and the implications on the MOVPE reactor hardware will be discussed.

[1] A. Bassal, S. Chevtchenko, F. Schnieder, T. Flisgen, O. Bengtsson, F. Brunner, and O. Hilt, Phys. Status Solidi A 2025, 2500406 (2025). [2] H. Qie, H. Gao, Y. Zhong, X. Guo, Q. Sun, T. Li, Y. Cao, X. Ge, X. Sun, F. Li, X. Sun, and H. Yang, Appl. Surf. Science 695, 162905 (2025).

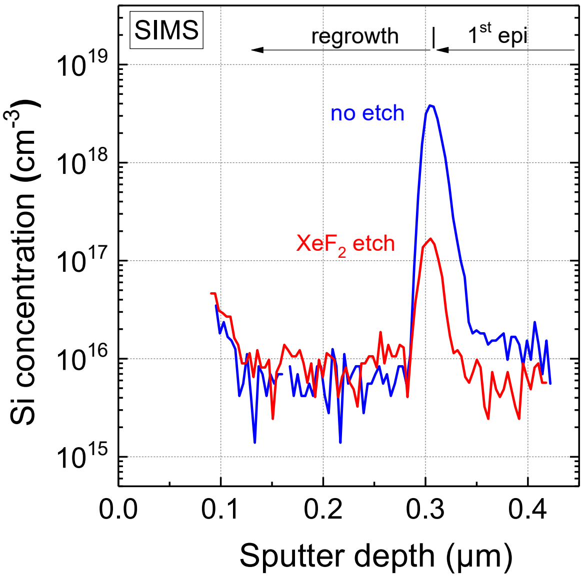

Fig. 1: SIMS measurement of Si concentration as a function of sputter depth.

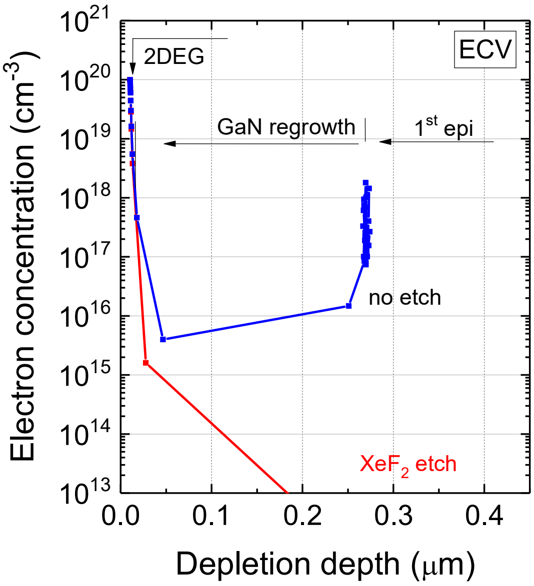

Fig.2: Electron concentration profiles measured by capacitance-voltage analysis.

Parts of the work were supported by the German Research Foundation (DFG) under project 514632983.

High-Temperature Annealing of AlN as Template for UV LEDs and Power Electronics in CO and NH_3 Containing Atmospheres

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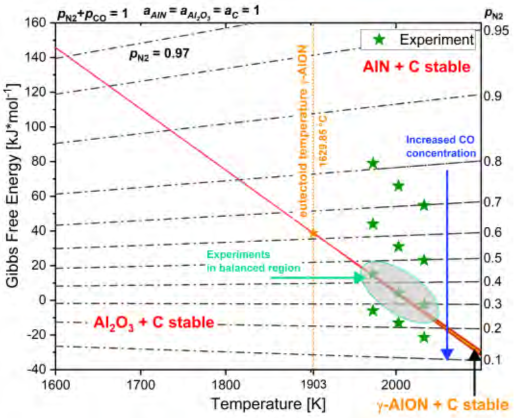
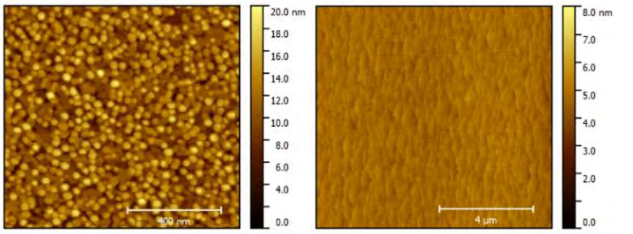
High-temperature-annealing (HTA) of aluminum nitride (AlN) on sapphire leads to high-quality AlN layers with threading dislocation densities < $5\cdot10^8$ cm^{-2}. HTA AlN as a heteroepitaxial template is therefore viewed as an interesting candidate for deep UV LEDs as well as AlN-based power electronics. In this work, we investigate the influence of reactive gas environments, including carbon monoxide (CO) during HTA at 1700 °C as well as a subsequent ammonia (NH_3) post-treatment at 1200 °C. To better understand the underlying complex mechanisms during HTA, the partial pressures of reactive gas species as well as the thermal decomposition of CO and NH_3 were modeled. In a first experiment, we analyzed different CO/N_2 ratios in the furnace atmosphere during HTA. This shifts the thermal equilibrium of the of the carbothermal nitridation reaction (CNR) $Al_2O_3 + 3\ C + N_2 \Leftrightarrow 2\ AlN + 3\ CO$ either towards the oxidation of AlN or nitridation of sapphire, depending on the CO/N_2 ratio. Increasing the CO partial pressure suppresses the formation of parasitic Al(O)N but simultaneously reduces the nitrogen partial pressure, leading to enhanced AlN destabilization near the wafer edges. This is due to the face-to-face configuration used in our experiments. Furthermore, an in-situ NH_3 treatment directly after HTA in the furnace has been investigated. Such a treatment might reduce the annealing time in the MOVPE reactor later on, by achieving a smooth, oxynitride-free growth front. Indeed, the in-situ NH_3 treatment has been found to drastically smoothen the AlN surface to RMS roughness values below 1 nm. A comparison between furnace-based NH_3 treatments and NH_3 cleaning in a MOVPE reactor prior to AlN regrowth, however, reveals significant differences: while MOVPE-cleaned templates yield homogeneous AlN regrowth, this is not observed for furnace-cleaned templates. This could, e.g., be related to residual AlON on the AlN surface arising by oxygen out-diffusion from the sapphire wafer during HTA. XPS surface analysis is currently in progress for clarification.





Left: Conducted processes (green) in the phase-stability diagram of the carbothermal nitridation reaction [1]. Right: AlN surface morphology after HTA w/o NH_3 treatment and smoothened by NH_3 cleaning at 1200 °C.

[1] Reconstructed from reaction enthalpy data in Nakao, W et al. J. Am. Ceram. Soc., 85, 889 – 896.

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Thursday, December 4th 2025, 9:40 – 10:40

Schinkelsaal

Arsenides & Phosphides : Growth & Characterization

9:40-10:00	Kleinschmidt - Measurement of PEC devices by in situ TRPL
10:00-10:20	Schygulla - MOCVD Reactor Quality Monitoring Using Double-Heterostructures
10:20-10:40	Shekarabi - TiO_2 Growth and Band Alignment on GaInP(100): Comparing P-rich to Oxidized Surfaces

Measurement of PEC devices by in situ TRPL

P. Kleinschmidt,[1,*] A. Omar,[1] S. Shekarabi,[1] D. Ostheimer,[1] and T. Hannappel[1]
[1]TU Ilmenau, Inst.of Physics, Fundamentals of Energy Materials, Ilmenau, Germany
*E-mail: peter.kleinschmidt@tu-ilmenau.de

Solar hydrogen is an essential part of the future energy mix based on renewable energies. As an alternative to the combination of photovoltaics plus electrolysis, direct unassisted photoelectrochemical (PEC) water splitting promises several benefits, e.g. reduced quantities of noble metal catalysts in the devices [1]. However, at present, several challenges remain, in particular stability of the devices in the electrolyte. In order to achieve high efficiencies, tandem structures are required, where one approach uses a silicon bottom cell and a III-V top cell.

For any minority charge carrier device such as solar cells, the charge carrier lifetime is a crucial quantity, as it enters the diffusion length and thereby determines charge carrier extraction. Time-resolved photoluminescence (TRPL) enables a direct measurement of this lifetime (specifically the effective lifetime), by recording the PL-response of the device after pulsed laser excitation.

Previously, we presented a TRPL setup (based on time-correlated single photon counting) for in situ measurement in the PEC environment. This setup features a remote measurement head which can be positioned directly in front of the optical access of the PEC chamber. Having completed tests using III-V-based double heterostructures, we performed measurements of different PEC devices in the electrolyte under operating conditions. Depending on the surface treatment of the structures we observed different behaviors of the TRPL signals. Specifically, using devices with a cap layer, we observed a decrease in the amplitude and a change in signal shape during operation in a regime where the electrical current was stable (figure 1). On the other hand, first measurements of devices without cap layer, but functionalized with a passivation layer and a catalyst exhibited a stable TRPL signal during the course of the operation. Hence, in situ TRPL is a sensitive method to detect local degradation in PEC devices.

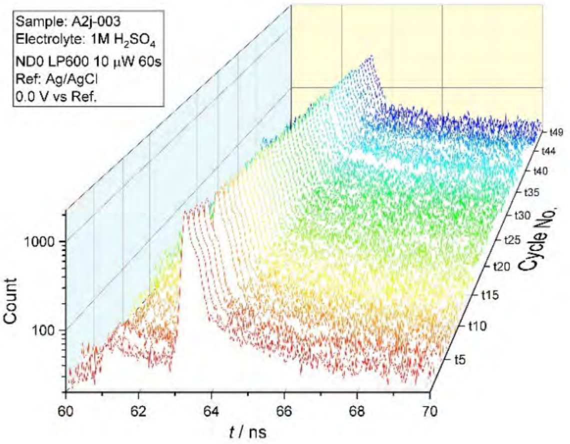

Figure 1: Decrease in TRPL signal during operation. During this time the electrical current remained stable.

[1] T. Rieth et al., Adv. Funct. Mater. 2025, e05106.

MOCVD Reactor Quality Monitoring Using Double-Heterostructures

P. Schygulla,[1,2]* N. Höner,[1] M. Klitzke,[1] and D. Lackner[1]
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A low impurity background density is essential for epitaxial growth of minority carrier devices such as high-efficiency multi-junction solar cells. Yet, maintenance work at an MOCVD machine such as exchanging reactor parts or replacing precursor material are a regular potential source of contamination. Here, we report on a monitoring procedure to quantify the reactor quality by determining the effective radiative efficiency of double-heterostructure (DH) test samples.

Oxygen atoms, a typical contaminant from exchanged reactor parts, form deep-level defects which reduce the minority carrier lifetime in GaInP or AlGaAs. Especially AlGaAs has by itself a high affinity to oxygen atoms. We decreased both V/III-ratios and growth temperatures compared to the standard growth protocol to enhance the incorporation of oxygen and thus to become more sensitive to potential contamination. First, reference samples were characterized by time-resolved photoluminescence (TRPL) and power-dependent relative PL (PDRPL) to determine the sample geometry dependent effective radiative recombination coefficient for this material [1, 2]. Then, this quantity was used to calibrate PDRPL measurements of subsequent DH samples, grown under various reactor conditions, and to obtain the effective radiative efficiency in different injection regimes. To assess the impact of oxygen we simulated a satellite exchange and compared the radiative efficiency for a sample sitting on a satellite that had been exposed to air to one on a reference satellite.

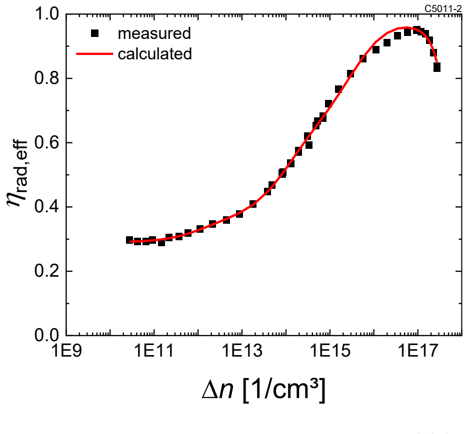

Figure 1. Effective radiative efficiency of an AlGaAs double-heterostructure determined by a calibrated PDRPL measurement (black points) and fitted curve assuming three defect levels (red solid line). The obtained excess carrier densities cover a relevant range for both one-sun and concentration applications.

[1] A. Walker, et al.: J. Appl. Phys. 119, 155702 (2016).

[2] P. Schygulla, et al.: J. Cryst. Growth 605, 127054 (2023).

TiO_2 Growth and Band Alignment on GaInP(100): Comparing P-rich to Oxidized Surfaces

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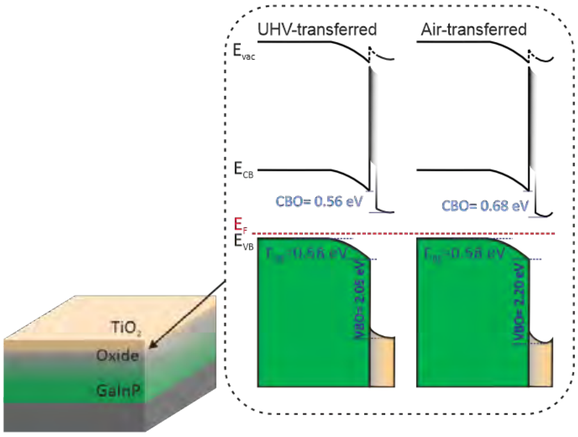
GaInP is widely used as a top absorber in tandem photoelectrochemical (PEC) and photovoltaic devices. However, GaInP and related III–V semiconductors are prone to photocorrosion, necessitating robust surface passivation for stable long-term operation. GaInP is particularly attractive due to its tunable lattice constant, favorable band structure, and suitable optical absorption properties [1]. To protect its surface against chemical degradation, TiO_2 passivation layers are often introduced on top of the GaInP surface. Plasma-enhanced atomic layer deposition (PE-ALD) of TiO_2 provides conformal coverage, high stability, and good charge transfer properties. However, to minimize interfacial losses, the electronic band alignment between GaInP and the TiO_2 layer must be investigated. In this study, we examine how the initial surface condition of GaInP, either an atomically well-ordered P-rich surface or a naturally oxidized surface, affects the interfacial chemistry and electronic structure during the TiO_2 deposition process. Angular-dependent photoemission spectroscopy reveals that although both starting surfaces evolve toward similar interfacial oxide compositions during ALD, the oxide on the well-defined P-rich surface remains a bit thinner. Despite this, the final interfacial chemistry and band alignment are nearly identical, indicating that the PE-ALD process itself predominantly governs interface formation. In summary, the initial surface condition mainly affects oxide thickness and composition, whereas the overall interfacial properties are defined by the ALD process, enabling reproducible TiO_2/GaInP heterostructures for stable and efficient PEC applications.



[1] Cheng, W.-H. et al., ACS Energy Lett. 2018, 3, 1795.

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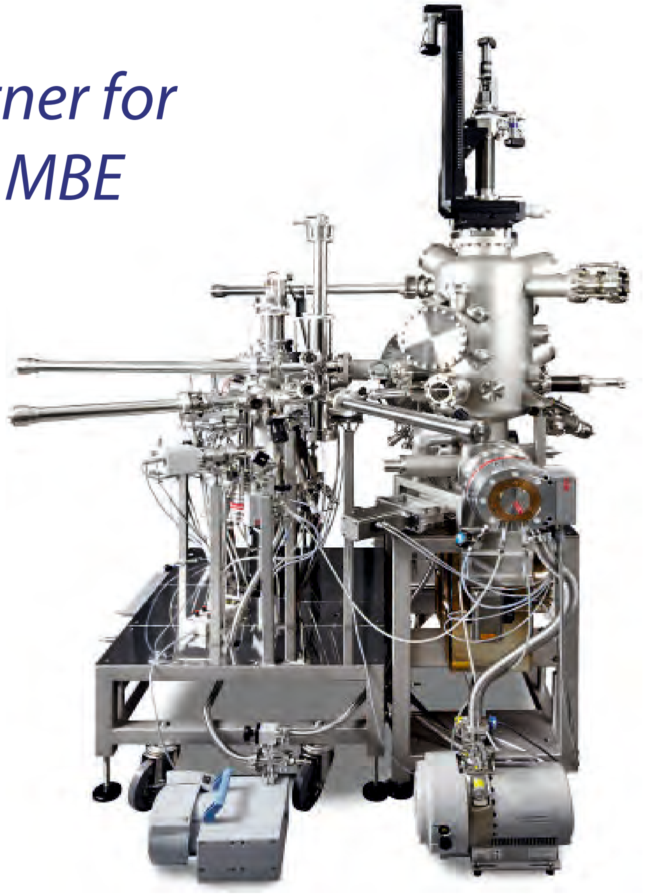

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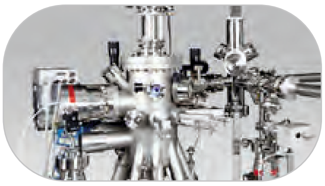

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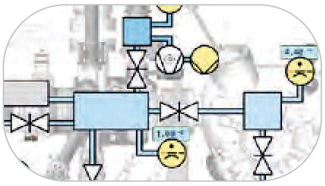

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Thursday, December 4th 2025, 11:40 – 13:00

Gartensaal

Arsenides : Growth

11:40-12:00	Henksmeier - Remote epitaxy of universal quasi-substrates
12:00-12:20	Darwish - MOVPE growth of InGaAs strain-balanced multi quantum well 0.66-eV absorber material for thermophotovoltaic applications
12:20-12:40	Kamath - Epitaxial Development of Resonant-Enhanced Interband Cascade Infrared Photodetectors for Mid-Infrared Gas Sensing Based on Ga-Free Superlattices
12:40-13:00	Vogt - Growth and Applications of InAs/GaSb T2SLs and Development of Ga-free InAs/InAsSb T2SLs by Molecular Beam Epitaxy

Remote epitaxy of universal quasi-substrates

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Recently, remote epitaxy was reported as a method for the fabrication of freestanding thin semiconductor membranes and host wafer recycling [1]. A thin 2D material layer on a semiconductor substrate induces an interaction gap between substrate and growing layer [2]. After growth, the epitaxial layer can be peeled off from the substrates allowing substrate re-usage, therefore reducing production cost of freestanding heterostructures and allowing fabrication of versatile stacked heterostructures of various material systems [1,2]. We present the fabrication of GaAs-2D-layer-GaAs quasi-substrates suitable for standard epitaxial overgrowth. An ultrathin 2D-like sp^2-hybridised amorphous carbon layer is deposited by plasma-enhanced chemical vapor deposition at low-temperature (300 °C) on a GaAs substrate. Fig 1a) shows dominant sp^2-hybridisation of the layer. Remote epitaxial overgrowth of this 2D-layer-GaAs template by molecular beam epitaxy is presented. The crystal quality and the surface morphology of 100 nm thick GaAs films grown at different temperatures (300 °C-600 °C) are analysed. Electron channelling contrast imaging (Fig. 1b)) and atomic force microscopy measurements (Fig. 1c)) reveal a threading dislocation density of 1×10^9 cm^{-2} and a smooth surface with a root-mean-square roughness of 0.2 nm on 1x1 µm^2 for optimised growth parameters. Further, InAs Stranski–Krastanov quantum dots buried in a GaAs matrix were epitaxially grown on the GaAs-2D-layer-GaAs quasi-substrates. Photoluminescence measurements (Fig. 1d)) reveal the good optical quality of the buried quantum dots.

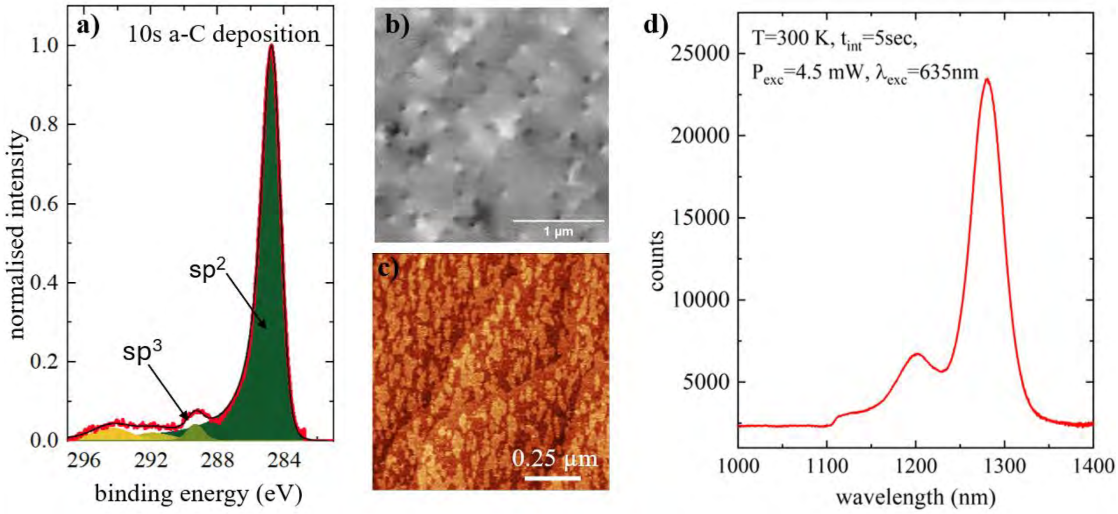

Fig. 1: Exemplary measurements as discussed in the main text.

[1] Kim, Y. et al. Nature 544, 340–343 (2017)

[2] Kong, W. et al. *Nat. Mater.* **17**, 999–1004 (2018)

MOVPE growth of InGaAs strain-balanced multi quantum well 0.66-eV absorber material for thermophotovoltaic applications

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Thermophotovoltaics (TPV) enables the direct conversion of long-wavelength photons from thermal radiation sources into electricity by means of the photovoltaic effect. Currently, there is an increased interest in such devices, driven by the prospect of large-scale thermal energy storage and waste heat recovery from industrial processes applications. To utilize low energy photons, low bandgap absorber materials are needed, which is of special relevance for comparatively lower temperature emitters. For the InGaAs alloy on InP, $In_{0.53}Ga_{0.47}As$ corresponds to the lattice-matched condition with a bandgap energy of 0.74 eV. The strain-balanced quantum well approach, consisting of alternating tensile and compressively strained layers, allows to realize absorber materials with even lower effective bandgaps without the need for metamorphic growth.

Here, we report on the MOVPE growth and characterization of $In_xGa_{1-x}As/In_yGa_{1-y}As$ multiple quantum wells with varying well and barrier compositions x and y, respectively, on InP substrates. The thicknesses of the respective layers were adjusted targeting strain-balancing. The quality of the well and barrier layers was investigated experimentally by high-resolution X-ray diffraction, atomic force microscopy and photoluminescence. A clear correlation between material quality and strain in the respective layers was found, with decreasing material quality with increasing strain.

First TPV test cells, with 10 to 20 quantum well periods were realized, with $In_{0.66}Ga_{0.34}As$ quantum well absorber layers of 14 nm thickness. The effective bandgap was demonstrated to be around 0.66 eV via photoluminescence measurements.

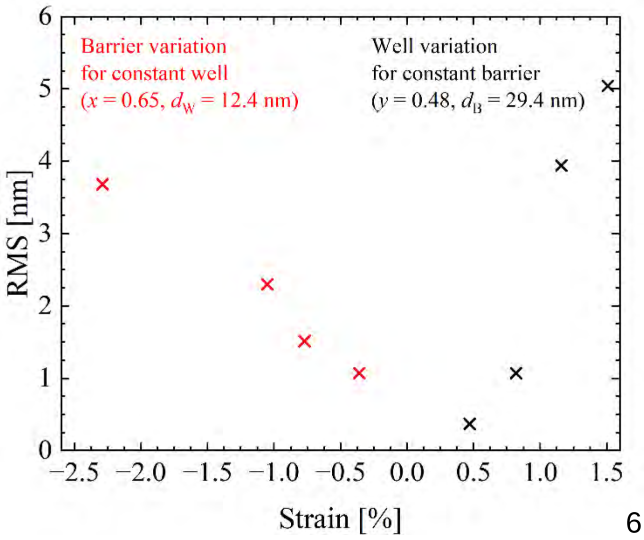

Figure 1. Surface roughness RMS (root mean square value) of $In_xGa_{1-x}As/In_yGa_{1-y}As$ multiple quantum well samples plotted against strain in the well (black points) and barrier (red points) layers, respectively.

Epitaxial Development of Resonant-Enhanced Interband Cascade Infrared Photodetectors for Mid-Infrared Gas Sensing Based on Ga-Free Superlattices

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Interband cascade infrared photodetectors (ICIPs) are promising for mid-infrared gas sensing due to their type-II band alignment, which enables efficient interband absorption and carrier extraction. Most ICIPs use Ga-containing superlattices, such as InAs/GaSb, which suffer from Ga-related defects that reduce carrier lifetimes and device performance[1]. Ga-free superlattices, such as $InAs/InAs_{1-x}Sb_x$, offer lower defect densities, improved transport, and longer diffusion lengths[2]. Embedding ICIP structures into resonant cavities, for example, with distributed Bragg reflectors (DBRs) allows photons to pass multiple times through the absorber, enhancing absorption and detectivity[3]. This increased absorption enables the use of shorter absorber lengths, thereby reducing dark currents, although it comes at the expense of a narrower wavelength response.

In this work, ICIPs with different number of stages (4, 8 and 12-stages) based on Ga-free $InAs/InAs_{0.75}Sb_{0.25}$ superlattices were grown using solid-source molecular beam epitaxy, targeting a cutoff wavelength of 5.5 µm. The structures were then processed into circular mesa devices with diameters ranging from 50 µm to 500 µm. Electro-optical measurements show that among the studied devices with 4, 8 and 12 stages (300 nm absorber layers per stage), the 8-stage ICIP exhibits the highest detectivity, reaching 5.92×10^8 Jones at 3.39 µm under room-temperature operation. To further enhance optical absorption, a three-stage ICIP structure was integrated into a 3λ/2 resonant cavity, using 10 pairs of GaSb/AlAsSb DBRs as the bottom mirror and the refractive index contrast between the cap layer and air serving as the top mirror (Fig. 1a). Fourier-transform infrared spectroscopy reveals a resonance dip at 4.2 µm (Fig. 1b), confirming the effect of the resonant cavity.

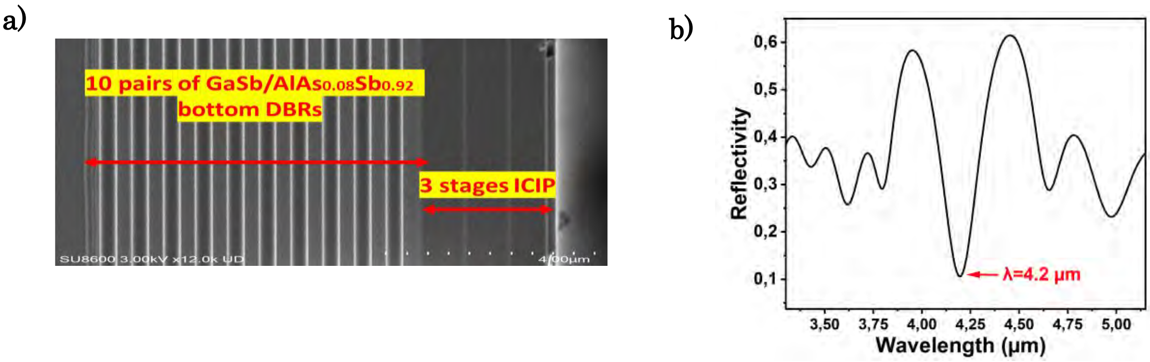

Fig.1: (a) Scanning electron microscope image of 10 pairs of GaSb/AlAsSb DBRs forming the bottom mirror of a 3λ/2 resonant cavity. (b) Reflectance measurement shows a resonance dip at 4.2 µm.

[1] E. H. Steenbergen, B. C. Connelly, et al., Appl. Phys. Lett. 99, 251110 (2011).
[2] A. Bader, F. Rothmayr, et al., Appl. Phys. Lett. 121, 041104 (2022).
[3] W. Huang, R. Q. Yang, J. Appl. Phys. 128, 214502 (2020).

Growth and Applications of InAs/GaSb T2SLs and Development of Ga-free InAs/InAsSb T2SLs by Molecular Beam Epitaxy

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The 6.1 Å materials family, which includes InAs, GaSb, and AlSb, as well as their ternary and quaternary alloys and corresponding type-II superlattices (T2SLs), enables broad wavelength tuning across the entire infrared spectrum (IR). By growing these T2SLs lattice-matched on GaSb-substrates using molecular beam epitaxy (MBE), we can effectively combine them to achieve specific requirements. At the IAF, various superlattices with different period thicknesses are grown lattice-matched on top of each other. The stacked superlattices are processed into bispectral detectors which can simultaneously detect infrared radiation of different wavelength ranges.

InAs/GaSb T2SLs have been successfully fabricated at IAF using up to 5 × 3″ or 4 × 4″ wafers in a multi-wafer MBE-system equipped with valved-cracker sources for As and Sb. However, precise control of the fluxes is essential, as the lattice mismatch of InAs to GaSb must be countered by introducing an InSb-like interface to achieve a strain-balanced epilayer. These thick structures are sensitive to defects and accurate control of the interfaces is essential to achieve the desired optoelectronic properties. A process developed at the IAF, which provides fast feedback on the performance of the grown material and the effects of adjustments in the epitaxy process, will be presented. On a process monitor piece cut out of a wafer pixels of various sizes are manufactured, and the optoelectronic performance at operating temperature is measured in a prober. Statistical methods are used to predict the number of defective pixels in a fully processed detector array, so that suitable modifications can be made to the epitaxy process.

InAs/InAsSb T2SLs show great potential, and our recent activities have focused on improving material quality and identifying optimal growth parameters. The growth of the layers is much simpler since only the Sb shutter needs to be moved during superlattice growth. The absorption wavelengths can be adjusted over a wide range by varying the period thickness while adjusting the Sb content. InAs/InAsSb T2SLs manufactured at the IAF exhibit a high minority charge carrier lifetime and a very low dark current density, enabling high operating temperatures (HOT).

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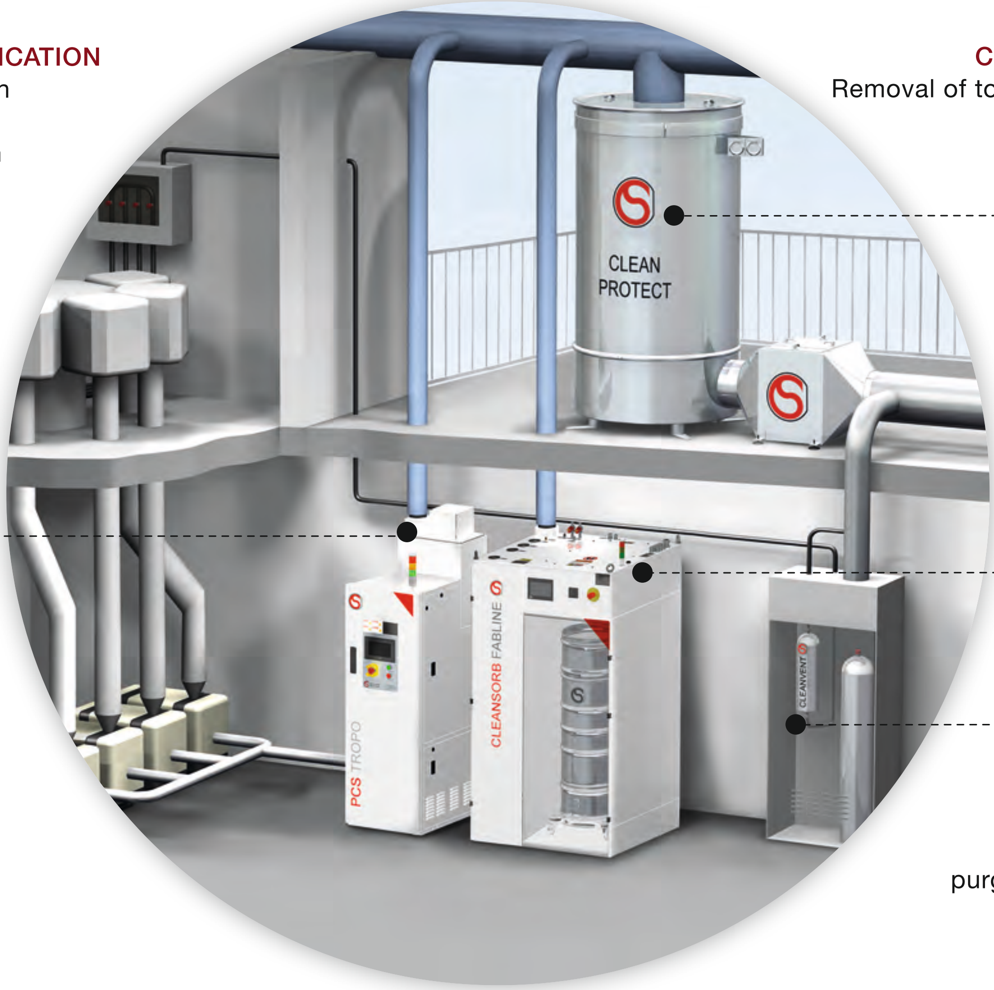

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Nitrides : Growth

11:40-12:00	Schörmann - AlScN pseudo-substrates for lattice-matched growth of high-In-content InGaN targeting red micro-LEDs
12:00-12:20	Rodmann - Porous GaN-Interlayers grown by MOVPE
12:20-12:40	Grigoletto - Influence of AlN/Sapphire Substrate Miscut on the Morphology and Threshold of 265 nm AlGaN DQW Laser
12:40-13:00	Beckmann - Progress on AIXTRON’s 200 mm InGaN-based Micro-LED Program

AlScN pseudo-substrates for lattice-matched growth of high-In-Content InGaN targeting red micro-LEDs

J. Schörmann,[1,]* M. F. Zscherp,[1] S. A. Jentsch,[1] M. Becker,[1] M. Stein,[1]
F. Meierhofer,[2] C. Margenfeld,[2] F. Winkler,[3,4] A. Beyer,[3,4] K. Volz,[3,4] A. Waag,[2] and
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Producing efficient red-emitting InGaN micro-LEDs is fundamentally limited by the large lattice mismatch between high-indium-content InGaN and conventional GaN substrates. This mismatch induces strain relaxation, defect generation, and compositional pulling, all of which impair optical performance. We propose using $Al_{1-x}Sc_xN$ as a pseudo-substrate to overcome these challenges by tuning its in-plane lattice constant to better match InGaN with high indium content.

We demonstrate plasma-assisted molecular beam epitaxy (PAMBE) growth of 120 nm thick, phase-pure $Al_{1-x}Sc_xN$ layers with Sc contents between 10–20 % on GaN templates. These AlScN templates exhibit relaxed growth and smooth surfaces (RMS roughness ~0.4 nm), making them suitable for overgrowth. InGaN layers with x_{In} = 0.28 and a thickness of ~100 nm were subsequently deposited on both AlScN and GaN reference substrates under identical conditions. Structural characterization via HRXRD reveals significantly improved crystalline quality, reduced dislocation densities, and complete suppression of compositional pulling in the InGaN grown on AlScN. Photoluminescence (PL) confirms the uniformity of indium incorporation for InGaN grown on AlScN exhibiting a single narrow emission at 538 nm, while the InGaN grown on GaN shows two peaks indicative of inhomogeneous In distribution. STEM-EDX further validates these findings, showing a homogeneous In profile for InGaN/AlScN and a pronounced composition gradient for the InGaN/GaN-grown reference without AlScN.

Our results demonstrate that AlScN pseudo-substrates are promising for future integrated red micro-LED devices.

[1] J. Schörmann et al., *ACS Appl. Mater. Interfaces* (2025)

Porous GaN-Interlayers grown by MOVPE

Leandra Rodmann[1], Sven Jachalke[2], Friederike Zimmermann[1], Roman Doradzinski[2],
and Thomas Mikolajick[1,3]

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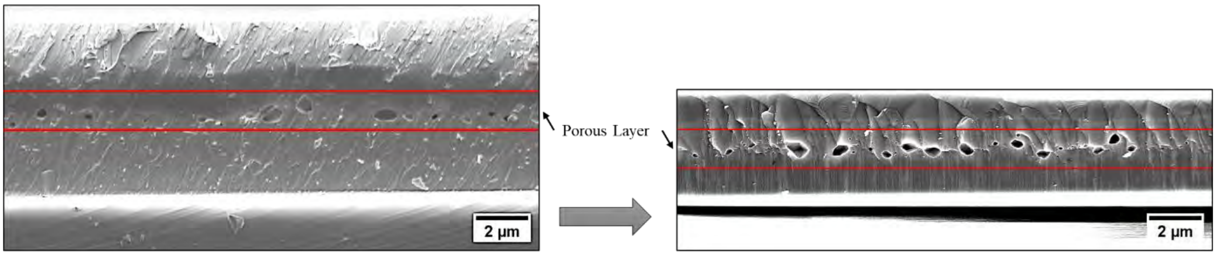
The heteroepitaxial deposition of thin Gallium Nitride (GaN) layers on sapphire substrates using metalorganic vapor phase epitaxy (MOVPE) is a standard method for producing templates for subsequent hydride vapor phase epitaxy (HVPE) bulk GaN growth. However, the significant lattice and thermal expansion mismatch between GaN and sapphire leads to substantial tensile stress and a high density of threading dislocations (TDs) in the GaN layer, which severely compromises material quality. Current solutions involve costly and time-consuming external post-template process steps (e.g., void assisted separation (VAS) [1], electrochemical etching [2]).

The objective of this work is to eliminate external processing by adapting the standard MOVPE template process with the in-situ growth of a porous GaN interlayer. Single and multiple layer GaN stacks were deposited on 3-inch sapphire substrates by MOVPE in order to identify growth conditions that favor void formation in GaN layers. The cross sections of the samples were characterized using scanning electron microscopy (SEM) to verify the presence of voids. We present here the successful formation of a void interlayer overgrown by a closed GaN layer (see Fig. 1 (left)). A multi-step process sequence involving controlled changes in temperature and pressure was identified to initiate and control the formation of voids within the GaN template. Furthermore, investigations revealed a correlation between void appearance and the in-situ tracked reflectance signal, enabling real-time process monitoring. These results provide the first insights into the targeted in-situ formation and modification (see Fig. 1 (right)) of porous GaN interlayers during MOVPE GaN growth.



first succesful sample

recent most promising sample

Figure 1: Current development stage of the formation of porous GaN interlayers during MOVPE GaN template growth. First successful formation of a void layer (left) and improved void density (right).

[1] Oshima *et al. Japanese Journal of Applied Physics* **42** L1 (2003)
[2] Yokoyama *et al. Applied Physics Express*, **17** (2024)

Influence of AlN/Sapphire Substrate Miscut on the Morphology and Threshold of 265 nm AlGaN DQW Laser

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Optically pumped AlGaN-based lasers emitting at 265 nm were grown by metalorganic vapor-phase epitaxy (MOVPE) on (0001) high-temperature-annealed (HTA) AlN/sapphire templates with substrate miscuts of 0.1° and 0.5° towards the m-direction, respectively. The laser heterostructure was comprised of an AlN buffer layer, an $Al_{0.75}Ga_{0.25}N$:Si cladding layer followed by 50 nm $Al_{0.63}Ga_{0.37}N$ lower and upper waveguides in which a 2x4.5 nm $Al_{0.51}Ga_{0.49}N$ double quantum well was embedded (Figure 1). For the structures on 0.1° offcut templates, the n-AlGaN cladding layer thickness was systematically varied from 0 to 1200 nm. Lasers without n-AlGaN cladding layer exhibited smooth, hillock-free step-flow growth and showed lasing at excitation power densities ~0.6 MW/cm² under optical pumping with a 193 nm ArF laser. In contrast, laser heterostructures with 800 nm and 1200 nm thick n-AlGaN cladding layers exhibit hillocks of diameter of 5 µm and 15 µm and height of 30 nm to 60 nm, respectively. The RMS roughness was 7.6 and 13.1 nm (scanned area: 25x25 µm²), which leads to significantly higher lasing thresholds > 8 MW/cm² (Figure 2). For laser on 0.5° offcut substrates, an 800 nm n-AlGaN cladding layer was grown under optimized conditions in order to produce smooth morphology and narrower terrace widths. AFM measurements show a significantly reduced RMS roughness of 1.2 nm with no observable hillocks. Optical pumping experiments on these laser structures showed performance comparable to those grown on 0.1° offcut templates without cladding. This work demonstrates that hillock-free AlGaN layers can be realized by tuning the miscut angle and supersaturation [1], controlled through V/III ratio, temperature, and growth rate.

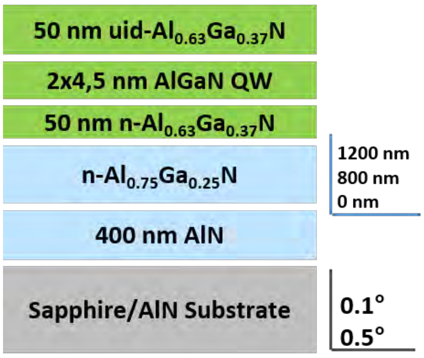

Fig. 1: Schematic of the optically pumped 265 nm laser heterostructures.

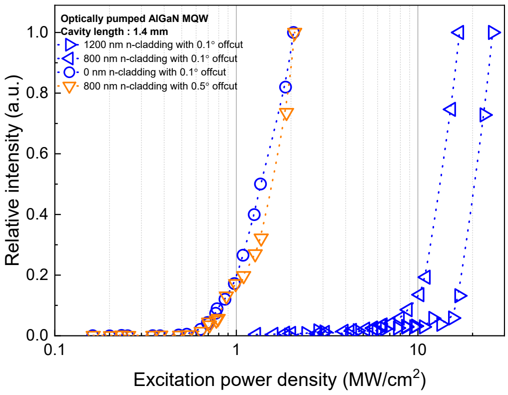

Fig. 2: Emission power of optically pumped lasers under pulsed excitation by a 193 nm ArF laser.

[1] W.K. Burton, N. Cabrera, F.C. Frank, Philos. Trans. R. Soc. Lond. Ser. Math. Phys. Sci. 243 (1997).

Progress on AIXTRON's 200 mm InGaN-based Micro-LED Program

Y. Beckmann[1], E. Hopmann[1], I. Booker[1], A. Boyd[1] and M. Heuken[1,*]
[1]AIXTRON SE, Dornkaulstr. 2, 52134 Herzogenrath, Germany
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Gallium Nitride (GaN) based micro-LED technology is considered next in line generation by combining high brightness, long operational lifetime, and energy efficiency to enable advanced applications such as augmented reality/virtual reality (AR/VR), automotive head-up-displays (HUDs), and wearable displays [1]. For mass production, MOCVD growth remains the most promising technique in terms of scalability, uniformity and compatibility with existing manufacturing infrastructure [2]. Optimization of MOCVD processes, through high growth rate and high throughput, has been shown to reduce manufacturing costs while maintaining performance, paving the way for commercially viable, cost-effective production of high-brightness InGaN micro-LED arrays [3].

We present our latest advancements in MOCVD technology towards mass production of InGaN-based micro-LEDs on 200 mm silicon substrates. Utilizing AIXTRON's Cl_2-assisted reactor cleaning process, we achieve high-quality GaN epitaxy with (002) FWHM of 402 arcsec and (102) FWHM of 420 arcsec at growth rates of up to 4.4 µm/h, while maintaining an ex-situ bow of the complete LED stack below 50 µm. For both blue (460 nm) and green (535 nm) InGaN-based LED fabrication, outstanding wafer-to-wafer and run-to-run reproducibility is delivered, with on-wafer emission wavelength and thickness uniformity standard deviations under 1 nm and 1 %, respectively. On 75 µm pixel blue mini-LED arrays, internal quantum efficiencies (IQE) of 77 % are achieved. Furthermore, our development paves the way toward red InGaN LEDs, with electroluminescence wavelengths surpassing 620 nm demonstrating the potential for full-color RGB integration.

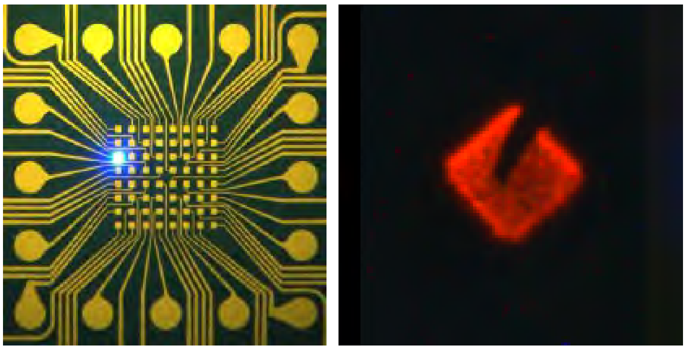

Figure 1: Electroluminescence of blue (left, Wafer processing by QubeDot GmbH, Germany) and red (right) InGaN-based LEDs

[1] A. Cheng et al.: Progress in Quantum Electronics; Vol. 102; 100575 (2025)

[2] H. Amano: Handbook of Crystal Growth (Elsevier), MOCVD of Nitrides (2015)

[3] Z. Li et al.: IEEE Open Journal of Immersive Displays; Vol. 1; 62 (2024)

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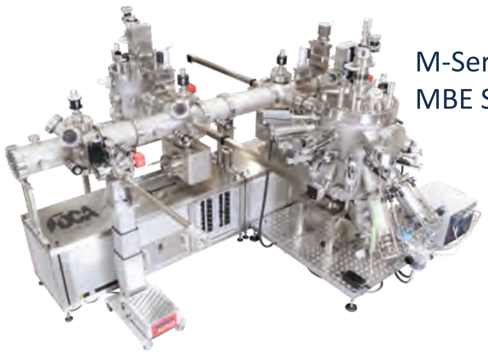

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Thursday, December 4th 2025, 14:10 – 15:30

Gartensaal

MBE of InGaAs QDs

14:10-14:30	Avdienko - MBE growth of electrically tunable asymmetric InAs/InGaAs QD-molecules emitting in O-band
14:30-14:50	Patane - Molecular Beam Epitaxy of Electrically Chargeable and Tunable Telecom C-Band Quantum Dots
14:50-15:10	Kersting - Low-density InAs quantum dots for telecom O-band single-photon emission
15:10-15:30	Krüger - Importance of Aluminium Quality for High-Quality Quantum Emitter

MBE growth of electrically tunable asymmetric InAs/InGaAs QD-molecules emitting in O-band

P. Avdienko,[1,]* L. Hanschke,[2] Q. Buchinger,[3] H. Riedl,[1] A. Pfenning,[3] T. Huber-Loyola,[3] S. Höfling,[3] K. Müller,[2] and J.J. Finley[1]*
[1]Walter Schottky Institute, Physics Department, School of Natural Sciences, TUM, Am Coulombwall 4, 85748, Garching b. München, Germany
[2]ZEIT Lab, School of Computation, Information and Technology, TUM, Hans-Piloty-Straße 1, 85748, Garching b. München, Germany
[3]Lehrstuhl für Technische Physik, Physikalisches Institut, Julius-Maximilians-Universität Würzburg, Am Hubland, 97074 Würzburg, Germany
*E-mail: *pavel.avdienko@tum.de and jj.finley@tum.de

Epitaxially grown semiconductor quantum dots (QDs) and QD-molecules are a basis for modern photonic quantum technologies. Compared to spin qubits in III-V QDs, singlet-triplet logical qubits in optically active QD-molecules have been recently shown to have enhanced coherence times, due to suppressed coupling to magnetic noise [1].

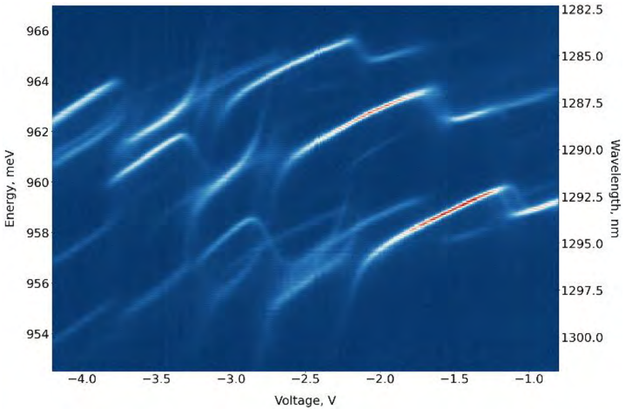

Fig.1 Bias-dependent μPL spectrum of InAs/InGaAs QDM

We present the first direct experimental observation of electrically tunable quantum orbital couplings and spin interaction in individual vertically stacked asymmetric InAs/InGaAs QD-molecules emitting in the O-band (Fig.1). Individual InAs QD layers were grown by MBE on GaAs(001) substrates and overgrown by a 7–8 nm $In_{0.25}Ga_{0.75}As$ strain-reducing layer. The InAs/InGaAs QD layers, separated by 3–10 nm GaAs barriers, were symmetrically positioned near the center of the intrinsic region of a p-i-n diode, enabling tuning of excitonic transition energies and orbital couplings. The QD layers were symmetrically situated by 5 nm GaAs, a 68 nm $Al_{0.75}Ga_{0.25}As$ barrier [2], and 90 nm GaAs layers before p- or n-GaAs layers. By tuning the internal electric field in the samples containing InAs/InGaAs QD-molecules emitting in the O-band, we observe clear anticrossings of different charge state transitions, including spin interaction. The correlation of MBE growth parameters with structural properties and optical properties of the developed QD-molecule heterostructures is discussed in detail.

[1] K. X. Tran et al., Phys. Rev. Lett. 129, 027403 (2022)
[2] A.J. Bennett, et al. Appl. Phys. Lett. 97(3), 031104 (2010)

Molecular Beam Epitaxy of Electrically Chargeable and Tunable Telecom C-Band Quantum Dots

M. Patanè[1]*, J. A. Walther[1], J. Kaupp[1], S. Estevam[1], M. Emmerling[1], S. Krüger[1],
T. Huber-Loyola[1,2], S. Höfling[1], and A. T. Pfenning[1]

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InAs Quantum Dots (QDs) grown on InP substrates are promising candidates as on-demand single-photon sources emitting in the telecom C-Band, where the low loss in standard fibers offers an advantage for scalable quantum communication and computation platforms [1]. In previous works, our group demonstrated Purcell enhanced single-photon emission from a QD emitting in the telecom C-band with high indistinguishability [2,3].

To further control the emission properties of the QDs, we grow InAs/InAlGaAs QDs within p-i-n and n-i-n diode devices to leverage the quantum-confined Stark effect and charge control capabilities offered by these structures [4]. The heterostructure design is optimized by calculating the conduction and valence band profile with a Schrödinger-Poisson solver (Fig. 1a). Initial results on tuning of the QDs emission are presented. A voltage-dependent redshift of the photon emission from the QDs is observed, as well as charge control (Fig. 1b).

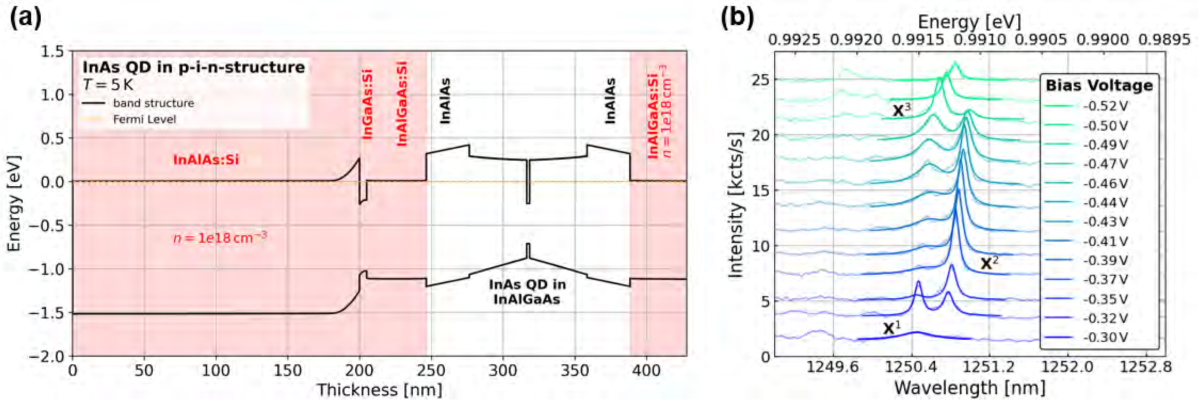

Figure 1. (a) 1D Simulation of the 0-Bias conduction and valence band profile of a n-i-n structure with QD-layer approximated as a potential well (b) Redshifts for X^2 and X^3 lines are observed in n-i-n device

[1] C. Couteau et al., Nat. Rev. Phys. 5, 326–338 (2023)

[2] J. Kim et al., Adv Quantum Technol. 8, no. 10 (2025): e2500069

[3] N. Hauser et al., arXiv:2505.09695 (2025)

[4] J. Zhang et al., Nano Lett. 17, 1, 501–507 (2017)

Low-density InAs quantum dots for telecom O-band single-photon emission

E. Kersting,[1,*] N. Spitzer,[1] H.G. Babin,[1] S. Krüger,[1] and A. Ludwig[1]
[1]Ruhr University Bochum, Experimental Physics VI, Bochum, NRW, Germany
*E-mail: elias.kersting@rub.de

InAs quantum dots (QDs) grown by molecular beam epitaxy (MBE) are promising candidates for single-photon sources (SPS), particularly for quantum communication. Emission in the telecom O-band (1260–1360 nm) is especially desirable due to the low transmission loss in optical fibers. However, conventional Stranski–Krastanov (SK) InAs QDs face challenges in achieving low and well-controlled densities in the range of 0.1–10 QDs/μm², as well as in precisely tuning the emission wavelength.

We present an alternative approach to address this issue based on local droplet etching (LDE), in which nanoholes in a GaAs matrix are filled with InAs to form QDs [1]. The quantum dot density is defined by the nanohole pattern, enabling precise and scalable control. A strain-reducing layer (SRL) shifts the emission wavelength into the telecom O-band. Homogeneous low-density (~2 QDs/μm²) growth is achieved through shutter-synchronized deposition (Fig. 1), making this approach well suited for scalable SPS fabrication [2]. We detail the fabrication method and present structural and optical characterization results.

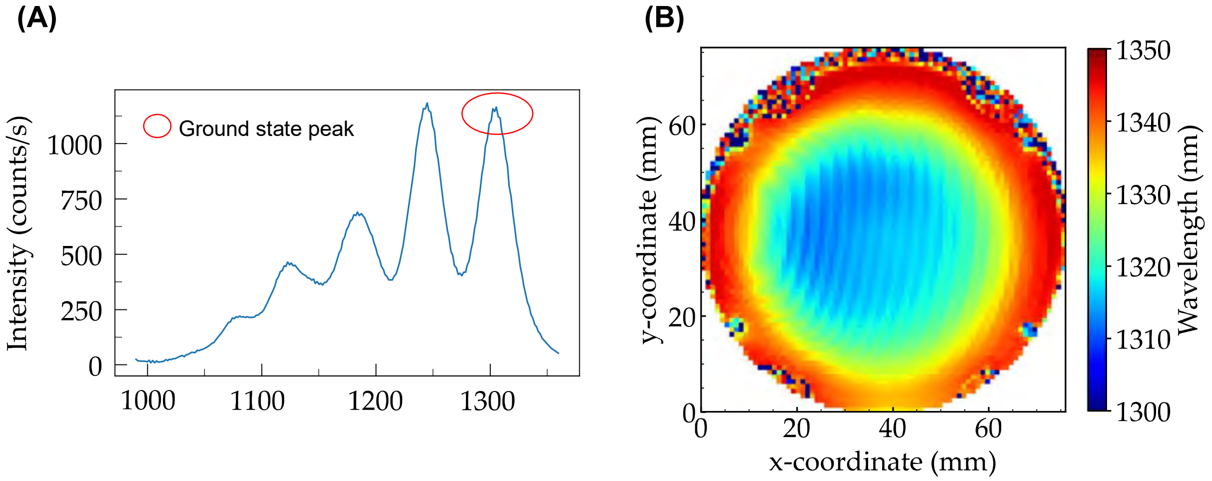

Fig. 1. (A) Photoluminescence (PL) spectrum recorded at the center of the wafer at 80 K. **(B)** PL map showing the ground-state peak wavelength across a full 3” wafer.

[1] N. Spitzer, E. Kersting, M. Grell, D. Kohminaei, M. Schmidt, N. Bart, A.D. Wieck, and A. Ludwig: Crystals 14, 1014 (2024).

[2] E. Kersting, H.-G. Babin, N. Spitzer, J.-Y. Yan, F. Liu, A.D. Wieck, and A. Ludwig: Nanomaterials 15, 157 (2025).

Importance of Aluminium Quality for High-Quality Quantum Emitter

Severin Krüger[1,2], Elias Kersting[1], Phil Badura[1], Arne Ludwig[1]
[1]Ruhr-University Bochum, EP VI, Bochum, North Rhine-Westphalia, Germany
[2]Sparrow Quantum Aps., Copenhagen, Denmark
*E-mail: severin.schmid@ruhr-uni-bochum.de

InAs quantum dots are regarded as excellent candidates for single photon emitters due to their high photon rates, good single photon properties, and compatibility with scalable and integratable photonic platforms.

Despite remarkable progress for quantum dots emitting at 950 nm, achieving the same results for quantum dots emitting in the important optical fibre transparency window around 1.3 µm has remained a major challenge.

Here we present a routine we used to monitor and improve the quality of aluminium containing layers grown in our MBE. We find that high quality Al in MBE significantly improves the interface quality and smoothness of Al(Ga)As layers by reducting the surface roughness.

These improvements enabled the growth of pristine distributed Bragg reflectors beneath a defect free, charge tunable quantum dot device, emitting near transform-limited single photons in the O-band at 1.3 µm.

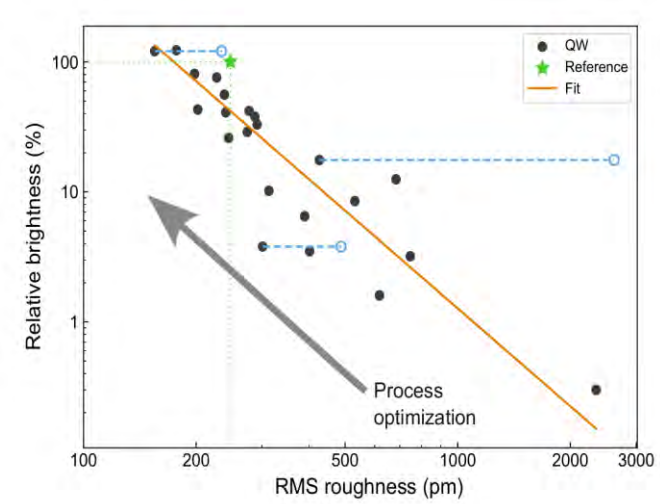

Figure 1: relation between brighness and roughness of grown QW structures [1]

[1] M. Albrechtsen *et al.*, “A quantum-coherent photon–emitter interface in the original telecom band,” *arXiv preprint*, arXiv:2510.09251, Oct. 2025. [Online]. Available: https://arXiv.org/abs/2510.09251

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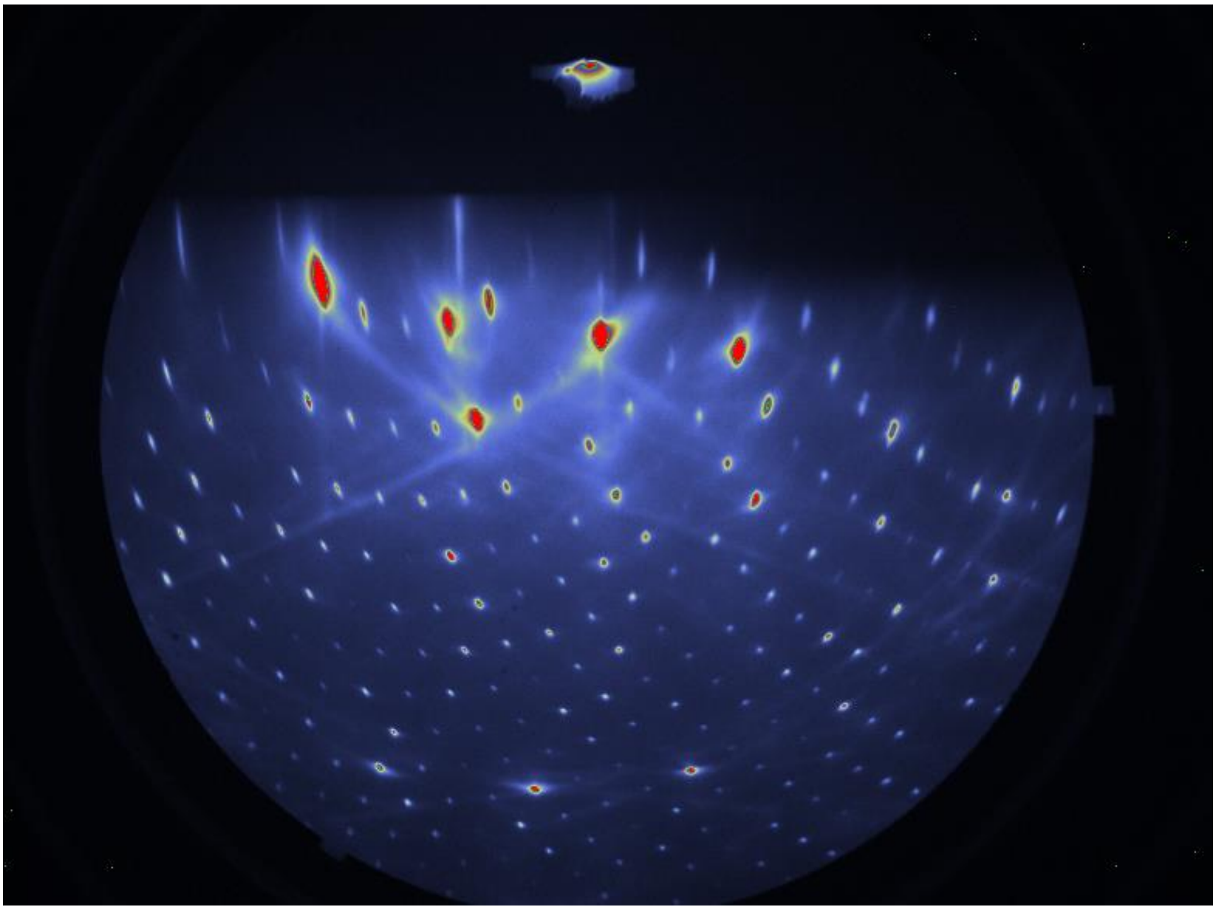

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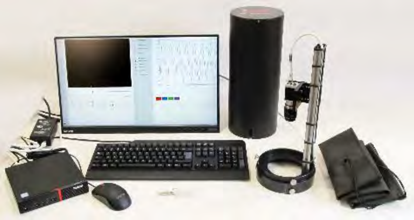

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RHEED Camera and
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High Pressure

Thursday, December 4th 2025, 14:10 – 15:30

Schinkelsaal

In-situ Growth Monitoring

14:10-14:30	Haberland - About the accuracy of in-situ metrology: Comparison of in-situ measured layer thicknesses in MOVPE with cross-section STEM
14:30-14:50	Hasanli - Advantages and Limitations of In-Situ Curvature Measurements During MBE Growth
14:50-15:10	Bastiman - Toward Agentic AI for MBE: A Unified AI, RHEED, and Control Software for Rapid GaN Growth Optimisation
15:10-15:30	Grutke - Optical In-Situ Response During Pulsed III–V Nucleation on Silicon

About the accuracy of in-situ metrology: Comparison of in-situ measured layer thicknesses in MOVPE with cross-section STEM

K. Haberland[1]*, T. Kolbe[2], F. Bertram[3], G. Schmidt[3], J. Christen[3], M. Weyers[2]
[1] LayTec AG, Seesener Str. 10-13, 10709 Berlin, Germany
[2] Ferdinand-Braun-Institut (FBH), Gustav-Kirchhoff-Str. 4, 12489 Berlin, Germany
[3] Otto-von-Guericke-Universität, Institut für Physik, Universitätsplatz 2, 39106 Magdeburg, Germany
*E-mail: kolja.haberland@laytec.de

Optical in-situ metrology is a well-established method in metalorganic vapor phase epitaxy (MOVPE). It is routinely used to measure wafer temperature, multi wavelength reflectance and wafer curvature in real time during the growth run. From the measured reflectance, several relevant layer properties such as growth rate, layer thickness, surface roughness and ternary composition can easily be extracted without the need to perform time consuming and sometimes destructive ex-situ characterization. But how precise and accurate are the results of in-situ growth analysis?

In this work we compared the results of the layer thickness analysis of the in-situ data with cross-section scanning transmission electron microscopy on the identical wafer. A MOVPE grown deep UV LED structure with emission wavelength around 230 nm was used for this purpose. These structures are complex and consist of differently doped $Al_xGa_{x-1}N$ layers with high Al-contents. Various layers, including the polarization doping layer and the active zone were analyzed, also taking advantage of short wavelength reflectance measurements, at 365nm and 280nm, that provide additional information. The results of the two methods (in-situ reflectance vs. STEM) agreed excellently within ±2nm, proving the high accuracy and benefit of the in-situ measurements as real-time and non-destructive metrology (see Fig. 1).

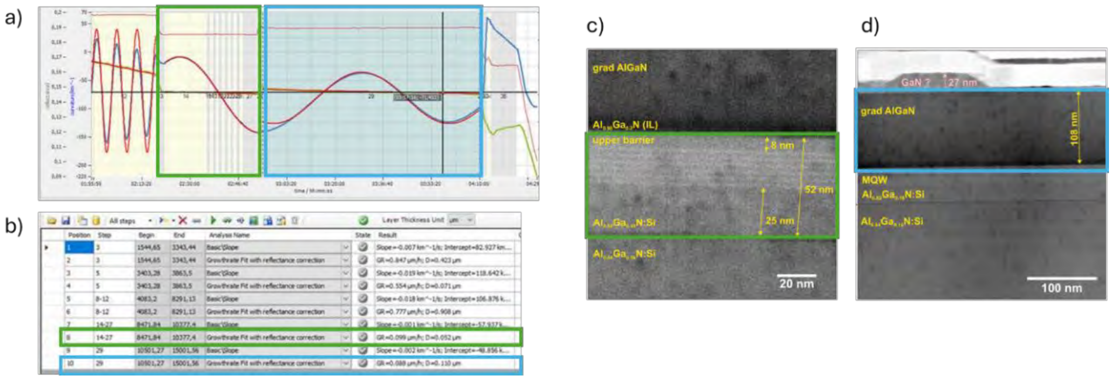


Fig. 1: a) In-situ reflectance data measured during epitaxy of a ~230nm emitting deep UV-LED. b) Results of growth rate and layer thickness analysis. c+d) STEM picture of the same wafer showing the layer thickness determined from the STEM measurement.

Advantages and Limitations of In-Situ Curvature Measurements During MBE Growth

I. S. Hasanli,[1,*] A. Kleinkamp,[1] S. Breuer,[1] Martin Schell,[1,2] and R. B. Kohlhaas[1]

[1] Fraunhofer Heinrich Hertz Institute, Einsteinufer 37, 10587 Berlin, Germany

[2] Technische Universität Berlin, Festkörperphysik, Hardenbergstr. 36, 10623 Berlin, Germany

* Email: intigam.soltan.hasanli@hhi.fraunhofer.de

In modern epitaxy, in-situ curvature measurements can be used to monitor the lattice parameters of growing layers [1]. Precise measurements and fast calculation loops can allow the grower to immediately react to any unwanted deviation from the target strain by readjusting sources. This approach is particularly appealing for InP epitaxy, where accurate lattice matching of ternary InGaAs and InAlAs layers is central to the correct functioning and high yield of many devices, such as photodetectors, lasers, mirrors, or transistors. Automatic Al source fine tuning using the curvature derivative was demonstrated last year for InAlAs grown on InP [2].

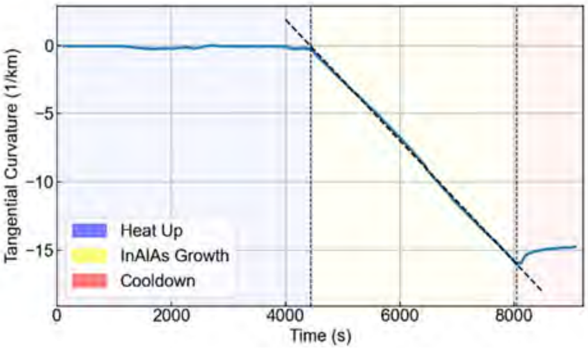


Figure 1. Curvature of InAlAs on InP (blue) and linear fit (black dashed line) with slope -4.45 × 10^{-3} $km^{-1}s^{-1}$.

We recently installed the commercial tool EZ-Curve on our Riber gas source MBE 412, which provides sufficient precision for similar control. For the feedback loop, we need to know the curvature derivative at growth temperature required for lattice matching at room temperature.

In our contribution, we present our calculations and subsequent experiments. Figure 1 shows the curvature of the InP wafer during MBE growth of an InAlAs layer. As expected, the curvature gradient is constant during InAlAs growth, indicating constant strain in the grown layer. Figure 2 provides a plot of calculated room temperature strain versus wafer curvature derivative at growth temperature as well as measurements of six InAlAs epitaxial layers grown at 350°C.

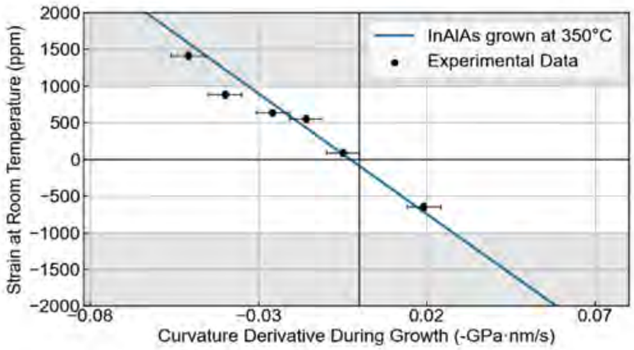


Figure 2. Room temp. strain vs curvature derivative at growth temp. for InAlAs on InP: calculation (blue line) and experimental results (black points).

We will demonstrate that controlling the curvature in-situ gives access to fine tuning the lattice matching. Since the curvature is directly proportional to the product of stress and thickness of the grown layers, limitations arise for thick samples, thin layers, and sudden temperature changes. We will discuss these challenges and ways of managing them.

[1] F. Brunner et al. Journal of Crystal Growth 298, 202–206 (2007).

[2] A. Arnoult et al., Automatic Lattice Mismatch Control, Webinar EZ-Curve, 2024. https://hal.science/hal-04820158v1/

Toward Agentic AI for MBE: A Unified AI, RHEED, and Control Software for Rapid GaN Growth Optimisation

F. Bastiman,[1,]* J. Kang, [2] L. Geelhaar[2], M. I. Lorente[1] and R. Engel-Herbert[2]

[1]Bizmuth MBE Ltd, London, UK

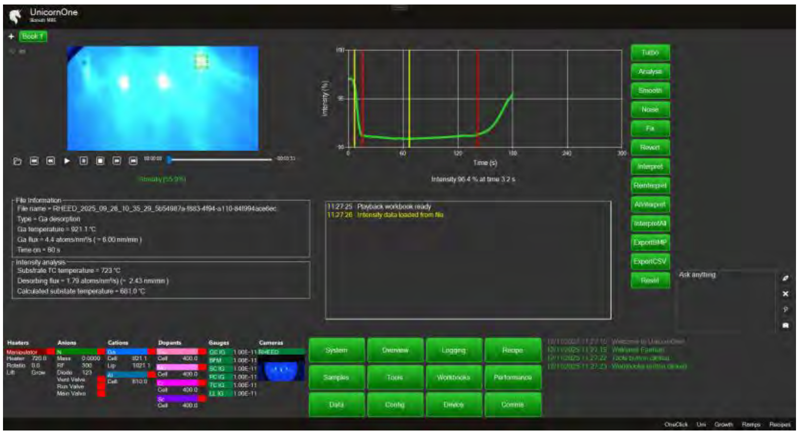
[2] Paul Drude Institute, Berlin, Germany

*E-mail: bastiman@bizmuthmbe.com

Gallium nitride (GaN) remains one of the most challenging III–V materials to grow reproducibly. Even under stable system conditions, the true sample temperature can deviate by **±100 °C** from the thermocouple reading, varying significantly from wafer to wafer. Because GaN growth is highly sensitive to substrate temperature, precise **flux control** is essential to maintaining the correct metal-rich regime—yet this control is only meaningful when the actual sample temperature is known.

We present a **single integrated software solution** that combines **RHEED analysis, full MBE control, and AI-driven decision-making** into a unified workbook. This system is capable of **calibrating the effective growth temperature and identifying optimal GaN growth conditions on any unknown sample within 33 minutes**.

The workbook coordinates multiple specialised AI models with a deterministic sequence of subtasks, forming a coherent, autonomous workflow. This represents a practical and significant step toward a fully **agentic AI for MBE growth**, where the system actively plans, executes, and optimises growth procedures.



File information
File name = RHEED_2025_09_28_10_35_29_5b54987a-f883-4f94-a110-84f994ace6ec
Type = Ga desorption
Ga temperature = 921.1 °C
Ga flux = 4.4 atoms/nm²/s (= 6.00 nm/min)
Time on = 60 s

Intensity analysis
Substrate TC temperature = 723 °C
Desorbing flux = 1.79 atoms/nm²/s) (= 2.43 nm/min)
Calculated substate temperature = 681.0 °C

Intensity 96.4 % at time 3.2 s

```
11:27:25  Playback workbook ready
11:27:26  Intensity data loaded from file
```

Figure 1: Screenshot of AI workbook analysing GaN RHEED envelope

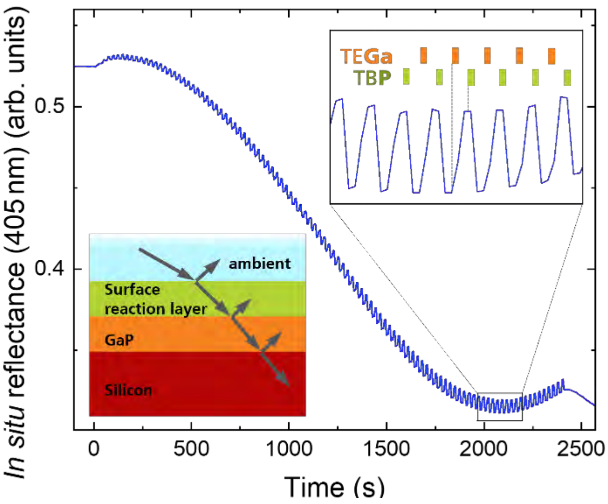
[1] G. Konmüller et al., *Appl. Phys. Lett.* 91, 161904 (2007)
[2] B. Heying, et al., *Journal of Applied Physics*, vol. 88, no. 4, pp. 1855 (2000)

Optical In-Situ Response During Pulsed III–V Nucleation on Silicon

J. Grutke,[1,2,]* A. W. Bett,[1,2] and J. Ohlmann[1]
[1]Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany
[2]University Freiburg, Physics Institute, Germany
*E-mail: jonas.grutke@ise.fraunhofer.de

Monolithic integration of III–V materials on silicon is a promising low-cost route for various applications. The nucleation layer is crucial for this heteroepitaxial approach. We investigate nucleation of GaP and AlP on Si due to the low lattice mismatch of 0.3% and 0.6% to Si, respectively. The seed layer is deposited by flow-modulated epitaxy at low temperatures with alternating pulses of group-III precursors and tertiarybutylphosphine (TBP), with intermediate purge steps. Samples were grown in an Aixtron CRIUS CCS MOVPE reactor on 4” Si(001) substrates with a 6° offcut towards (111) at temperatures between 400 and 500 °C.

Our LayTec EpiCurve®Twin TT setup enables optical *in situ* measurements of substrate temperature, growth rate, and wafer curvature. During pulsed nucleation, we observe an additional reflectance oscillation that correlates with the pulse sequence. The reflectance increases during triethylgallium (TEGa) exposure and recovers only after the TBP pulse (see Figure). This behavior is consistent with the adsorbate-induced optical effects reported by Bachmann *et al.* [1], based on a model that includes a surface reaction layer comprising physisorbed and reacting precursors. The optical response of the surface reaction layer is dose-dependent for TEGa and persists over many pulses, indicating the formation of a quasi-stable surface layer. In contrast, trimethylgallium (for GaP growth) and trimethylaluminium (for AlP growth) produce no measurable reflectance modulation, implying either rapid reaction-desorption cycles, minimal steady-state coverage, or optically thin reaction products under these conditions.



The *in situ* reflectance of a pulsed GaP seed layer on silicon exhibits two oscillations: An envelope (Fabry-Pérot interference) describing growth rate of the film and a finer structure correlating to the pulsing sequence. The change can be described by thin film intereference based on a surface reaction layer [1].

These results support the value of in-situ reflectance as a probe of precursor-specific surface reactions during III–V/Si epitaxy and provide insight into the decomposition kinetics and reaction residues of various group-III precursors.

[1] K. J. Bachmann *et al.*, J. Vac. Sci. Technol. B, Vol. 14 (4), pp. 3019ff (1996)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Thursday, December 4th 2025, 15:30 – 16:10

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15:30-16:10 **Invited: Heuken - Review on several years of Innovation in Metalorganic Chemical Vapor Phase Deposition (MOCVD)**

Review on several years of Innovation in Metalorganic Chemical Vapor Phase Deposition (MOCVD)

Prof. Dr.-Ing. Michael Heuken

AIXTRON SE, Dornkaulstrasse 2, 52134 Herzogenrath, Germany

RWTH Aachen University, Sommerfeldstrasse 18, 52074 Aachen, Germany

Compound semiconductor devices - such as those made from materials like Gallium Arsenide (GaAs), Indium Phosphide (InP), and Gallium Nitride (GaN) play a crucial role in advancing technologies that align with several United Nations Sustainable Development Goals. To enable high speed or high power transistors, LED for solid state lighting applications or advanced multi junction solar cells we developed the Metalorganic Chemical Vapor Phase Deposition (MOCVD or MOVPE) technology for III-As/P/N based structures in MOCVD-systems ranging from small scale horizontal tube reactors to large production reactors. This technology enables the industrial introduction of high-volume device families which require dedicated layer sequences with specified properties uniformly distributed across wafer diameter up to 300 mm. However, some materials systems such as wideband gap II-VI materials or ZnO based structures never fulfilled their expectation despite extensive MOCVD growth effort.

The requirements for the process equipment are manifold, demanding utmost control of purity, composition and interfaces, dopant and layer thickness uniformity and low defect density of the epitaxial quantum structures. Besides layer quality, the ability to manufacture the device layer stacks reproducibly and economically is crucial to support the growing demand.

The focus of epitaxy production technology developments based on scientific understanding has been put on material properties close to the physical limit, improved process control, productivity enhancement concepts like wafer level automation, in-situ metrology to acquire process data for smart system control and predictive maintenance concepts. Recent progress in cost-down strategies and improved technical specifications will be reported here and will be compared to the technology status about 40 years ago. The application of the underlying physical, technical and chemical fundamentals support the engineering approaches to achieve economic, technical, and scientific objectives.

The application of the detailed understanding of the fundamentals of MOCVD, consequently designing and optimizing epitaxial equipment and processes and managing their transfer to industry will be explained by using several examples and it will be discussed how they developed over the last 40 years.

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Thursday, December 4th 2025, 17:10 – 18:30

Schinkelsaal

InGaAs-based Lasers

17:10-17:30	Noack - Gain and Absorption of MOVPE grown InGaAs Quantum Dot based Laser Devices for Emission in the NIR
17:30-17:50	Rühle - First Investigations of ASE for a seeded 1064 nm MEXL
17:50-18:10	Mukhangali - Single-layer high-density quantum dot lasers at 900-920 nm for low repetiton rate monolithic mode-locking
18:10-18:30	Baraz - In-situ EBL Fabrication and Characterization of Highly Homogeneous Micropillar Laser Arrays for Neuromorphic Computing Applications

Gain and Absorption of MOVPE grown InGaAs Quantum Dot based Laser Devices for Emission in the NIR

Philipp Noack*, Michael Jetter and Peter Michler
Institut für Halbleiteroptik und Funktionelle Grenzflächen (IHFG), Universität Stuttgart, Integrated Quantum Science and Technology (IQST),
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Data transmission using the Telecom O-Band is of great interest for development and research on digital infrastructure and data centers. Manufacturing these light sources on wafer scale using III-V compounds is still a challenge because of the large lattice mismatch between materials with small band gap e.g. InAs or GaSb and common GaAs substrates. InGaAs quantum dot based light sources can cover this wavelength range, while being grown on GaAs or even Silicon substrates.

Additionally, they can profit from unique advantages like lower carrier diffusion, improved thermal performance and fast gain recovery times [1]. Especially MOVPE grown quantum dots inherently offer broad gain spectra.

We present InGaAs quantum laser diode structures grown by MOVPE with varying number of QD layers and perform an investigation of the gain and absorption characteristics, utilizing the segmented contact method [2]. Devices with varying number of vertically stacked quantum dot layers are directly compared to isolate influence from quantum dot layer growth.

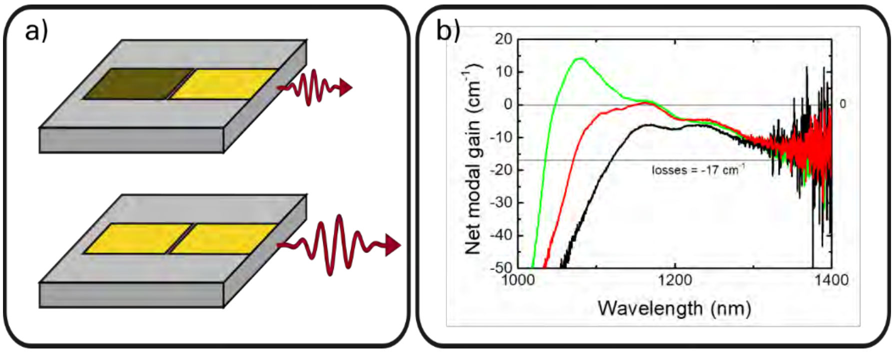

Figure (1): a) Schematic principle of the segmented contact method for measuring gain and absorption in laser diodes with unpumped (dark yellow) and pumped (bright yellow) segments.
b) Example for calculated net modal gain from a corresponding measurement for low (black), middle (red) and high (green) current density.

[1] C. Shang, Perspectives on Advances in Quantum Dot Lasers and Integration with Si Photonic Integrated Circuits. Bowers ACS Photonics 2021 8 (9), 2555-2566

[2] P. Blood, G, Characterization of semiconductor laser gain media by the segmented contact method, in IEEE Selected Topics in Quantum Electronics, vol. 9, no. 5, pp. 1275-1282, 2003

First Investigations of ASE for a seeded 1064 nm MEXL

R. Rühle[1,2,*], R. Bek[3], M. Jetter[1,2], and P. Michler[1,2]
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[2] Center for Integrated Quantum Science and Technology (IQST) and SCoPE, University of Stuttgart, Stuttgart, Germany
[3] Twenty-One Semiconductors GmbH, Neckartenzlingen, Germany
*E-mail: r.ruehle@ihfg.uni-stuttgart.de

For sensing with Rydberg atoms, tunable laser wavelength with a small linewidth and suitable output power at the atom transistion are needed. In order to minimize the setup, a tunable seed laser can be used, which will then be amplified by a nm Membrane-External Cavity Surface Emitting Laser (MECSEL). Compared to other set-ups, this semiconductor membrane amplifier has the advantages of high output power [1] with a high beam quality ($M^2 < 1.06$) [2] compared to other setups.

A MECSEL emitting at 1064 nm was grown via MOVPE in an Aixtron 3x2" closed-coupled showerhead reactor on a 4" (100) GaAs Substrate. It consists out of InGaAs QWs for emission at around 1064 nm. After processing, the MECSEL structure including heatspreader was mounted in a test setup.

First optical investigations, were performed with a 1064 nm tunable seed laser from Toptica. By pumping an MECSEL-Chip with an 808 nm pump laser, the incident angle of the seed laser was varied between angles of 10° to 90° and the photoluminescence was detected in the direction of the later laser output. Furthermore, direct incidence measurements of the seed on the MECSEL were performed. We show next to the fabrication of the structure as well the first optical characteristics of the device

With these pre-characterizations a complete MECSEL-resonator with a seed laser can be build up and further investigations can be executed.

[1] D. Priante, M. Zhang, A.R. Albrecht, R. Bek, M. Zimmer, C. Nguyen, D. Follman, G.D. Cole, and M. Sheik-Bahae: Electronics Letter 57, 337 (2021)

[2] H. Kahle, C.M. Mateo, U. Brauch, P. Tatar-Mathes, R. Bek, M. Jetter, T. Graf, and P. Michler: Optica 3, 1506 (2016)

Single-layer high-density quantum dot lasers at 900-920nm for low-repetiton rate monolithic mode-locking

Sungat Mukhangali[1], Sebastian Krüger[1], Martin Sturm[2], Martin Kamp[1], Sven Höfling[1]
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Monolithic low-repetition-rate mode-locked lasers are of growing interest for high-power ultrafast applications, owing to their compactness and potential for photonic integration [1,2]. However, their performance is often limited by restricted gain bandwidth, waveguide dispersion, nonlinear effects such as self-phase modulation, and amplified spontaneous emission noise. High-gain quantum-well active regions further induce large differential gain and saturation effects that destabilize mode-locking [3-5].

We report a monolithic passively mode-locked laser incorporating a single layer of high-density ($5–7\times10^{10}$ cm^{-2}) self-assembled AlGaInAs quantum dots (QD) embedded in a GRINSCH large-optical-aperture waveguide engineered for 900–920 nm operation [6]. The laser structure was grown by solid-state molecular beam epitaxy on GaAs:Si (001) substrates and consists of a 200 nm n-GaAs buffer, 1500 nm n-$Al_{0.4}$GaAs cladding, a 1000 nm GRINSCH waveguide with the QD active region at its center, a 1500 nm p-$Al_{0.4}$GaAs cladding, and a 200 nm p$^+$-GaAs cap. The GRINSCH waveguide was implemented via a short-period $Al_{0.33}$GaAs/GaAs superlattice with graded Al content (30–15%). Doping followed a graded Si/C ladder profile. Quantum dot ensemble is highly homogeneous showing narrow gaussian distribution and high surface density confirmed by AFM measurements (figure 1.1). Laser diodes processed in broad-area configuration giving high internal quantum efficiency of 95% and low internal losses 1.8 cm^{-1} evaluated by length-dependent measurements (figure 1.2).

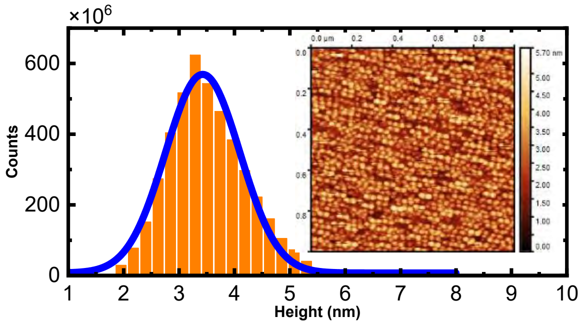

Figure 1.1. Quantum dot height distribution and surface density (insert).

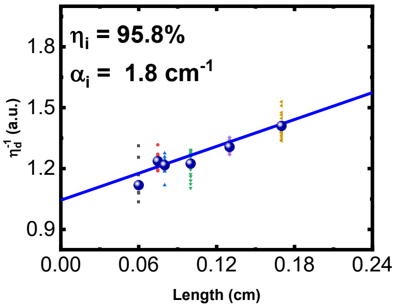

Figure 1.2. Evaluated intrinsic quantum efficiency and intrinsic losses

[1] Y. Li, M. Breivik, C.Y. Feng, B.O. Fimland, and L.F. Lester: IEEE Photonics Technology Letters 23, 1019 (2011).
[2] T. Xu, J. Cao, and I. Montrosset: Nanoscale Research Letters 10, 26 (2015).
[3] E.U. Rafailov, M.A. Cataluna, and W. Sibbett: Nature photonics 1, 395 (2007).
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[5] K. Yvind, D. Larsson, L.J. Christiansen, C. Angelo, L.K. Oxenlwe, J. Mrk, and J. Hanberg: IEEE Photonics Technology Letters, 16, 975 (2004).
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Presenting author email address: sungat.mukhangali@uni-wuerzburg.de

In-situ EBL Fabrication and Characterization of Highly Homogeneous Micropillar Laser Arrays for Neuromorphic Computing Applications

S. Baraz,[1,*] K. Gaur,[1] C.-W. Shih,[1] D. Brunner,[2] S. Rodt,[1] A. Koulas-Simos,[1] I. Limame,[1] and S. Reitzenstein[1]
[1] Institute of Physics, Technische Universität Berlin, 10623 Berlin, Germany
[2] Département d'Optique P. M. Duffieux, FEMTO-ST, Université Bourgogne Franche-Comté, CNRS UMR 6174, Besançon, France
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The demand for alternative computing architectures is rapidly increasing as classical hardware reaches its physical and economic limits, especially in fields such as artificial intelligence and machine learning. Inspired by principles of neuroscience and the demonstrated potential of photonic devices for ultrafast, energy-efficient neuromorphic processing [1][2], we present a scalable nanophotonic platform for reservoir computing, based on large arrays of highly homogeneous micropillar lasers fabricated via in-situ electron beam lithography (EBL) and optimized MOCVD growth.

This work demonstrates the design, growth, and patterning of 900 InGaAs quantum-dot-based micropillar resonators as depicted in Fig.1 (a), achieving low lasing thresholds (down to 20 μW) and enhanced spectral uniformity suitable for all-optical neuromorphic processing. In-situ cathodoluminescence mapping and EBL enable precise diameter tuning, followed by photoluminescence characterization of the resulting arrays (Fig. 1 (b)). The approach provides a robust route to large-scale, cost-effective arrays with high performance, advancing the prospects for next-generation neuromorphic computing hardware.

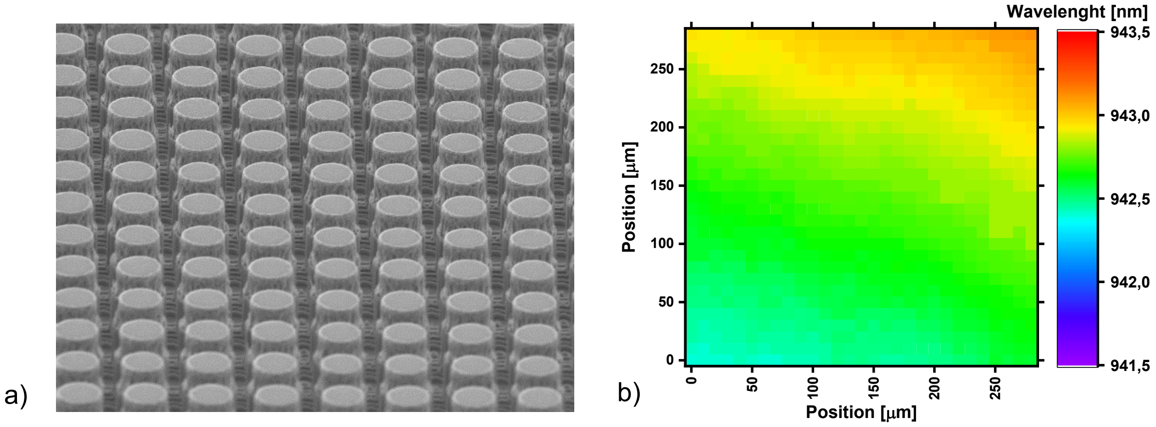

Fig. 1. (a) SEM image of micropillar laser array with diameter-tuned resonators. (b) Heatmap showing the spectral emission uniformity across the array, demonstrating improved homogeneity.

[1] A. Skalli et al., Opt. Mater. Express 12, 2395 (2022)
[2] T. Heuser et al., APL Photonics 3, 116103 (2018)

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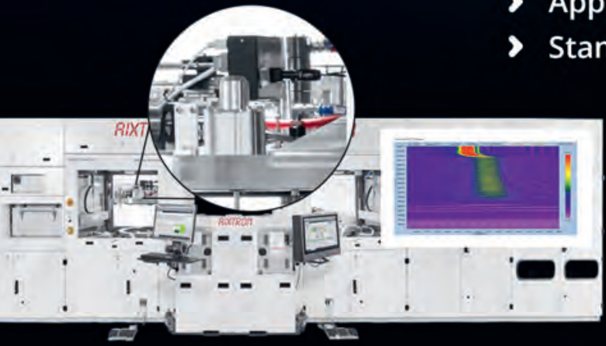

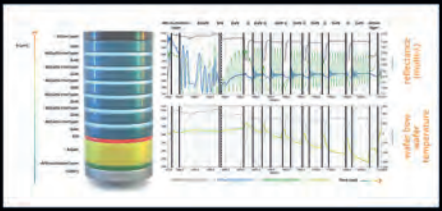

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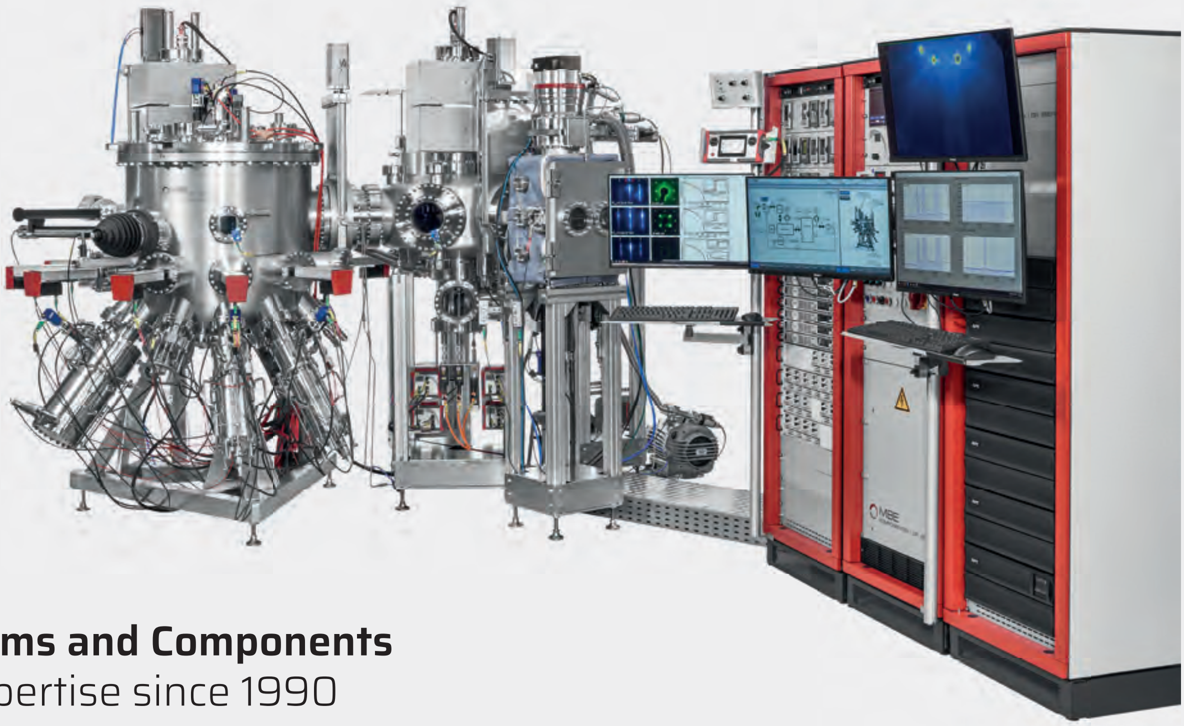

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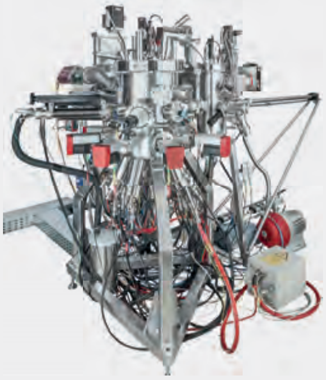

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Friday, December 5th 2025, 9:00- 10:40

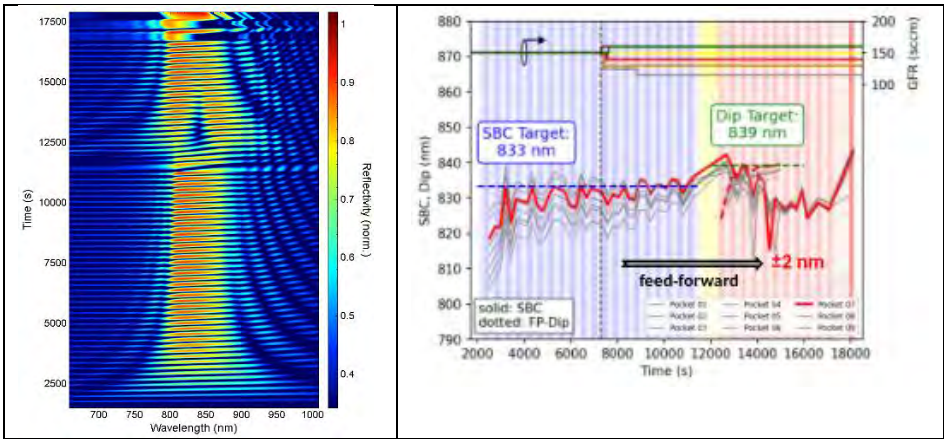
	Gartensaal
9:00-9:40	**Invited: Weyers - Broad range of specifications, low volume: efficient production of device heterostructures by MOVPE at FBH**
9:40-10:00	As - Remote Epitaxy of cubic Gallium Nitride on 3C-SiC (001) Substrates using amorphous Carbon Films
10:00-10:20	Zscherp - Mechanism of self-assembled cubic InGaN/GaN quantum well formation and bulk InGaN layers in metal-modulated molecular beam epitaxy
10:20-10:40	Jentsch - Cubic InGaN for Red Emission: Improved Phase Stability and Emission Properties by Metal-Modulated Epitaxy

Broad range of specifications, low volume: efficient production of device heterostructures by MOVPE at FBH

M. Weyers
Ferdinand-Braun-Institut (FBH), Berlin, Germany
*E-mail: markus.weyers@fbh-berlin.de

At FBH device heterostructures are being produced for the internal needs in projects but also for external customers. Usually, the required volumes can be covered by just one growth run in our multiwafer reactors. In order to obtain a high yield of devices within the specifications (that sometimes are very tight) without the need for many calibration runs, the whole MOVPE process needs to be well under control. This relates to layer purity that is warranted by qualification of each gas bottle and bubbler for TMGa and TMAl as well as the reactor after bigger maintenance work. To this end for GaAs-based growth a test laser structure at 730 nm that has been found sensitive to contamination is grown, processed and characterized. Additionally, the content of S is assessed since even small amounts that do not affect the basic laser performance are suspected to cause lifetime problems.

The status of the MOVPE tool is continuously monitored by analysis of the log files of specific steps like heat up/cool down or pumping down/filling up of the reactor and also for example the noise on signals from mass flow controllers. This allows for preventive maintenance before growth runs fail. Standard building blocks in the process recipes warrant the avoidance of e.g. sudden pressure changes and also allow for tracking across different recipes. Intensive use of in-situ-analytics with comparison to “golden runs” or simulation allows for early detection of any deviation. For VCSELs with very tight wavelength specs requiring a high accuracy in the optical thickness of the cavity, the reflectance data obtained during growth of the bottom n-DBR mirror are evaluated waferwise “on the fly” and the subtle differences in growth rate wafer-to-wafer are used to adjust the rotation flow for each satellite in the AIXTROn G4 reactor in order to narrow down the wavelength spread.



Left: Spectrally resolved reflectance during growth of a VCSEL structure
Right: wafer resolved transients of stop band center of n-DBR used for correction to tighten distribution of cavity resonance dip and thus emission wavelength

Remote Epitaxy of cubic Gallium Nitride on 3C-SiC (001) Substrates using amorphous Carbon Films

D.J. As,[1,]* P. Mahler,[1] T. Henksmeier[1] and D. Reuter[1]
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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 10^9cm^{-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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[2] As D.J. et al., *in Molecular Beam Epitaxy, 2nd Ed., Chapter 6, 95 (2018)*
[2] Littmann M. et al., *Phys. Stat. Sol.* B, **260**, 2300034 (2023)
[3] Henksmeier T. et al., *Communications Materials* **5**, 276 (2024)

Mechanism of self-assembled cubic InGaN/GaN quantum well formation and bulk InGaN layers in metal-modulated molecular beam epitaxy

Mario F. Zscherp[1]*, Silas A. Jentsch[1], Vitalii Lider[2], Matthew Chia[1,3], Andreas Beyer[2], Anja Henss[1], Donat J. As[4], Kerstin Volz[2], Sangam Chatterjee[1], and Jörg Schörmann[1]
[1] Institute of Experimental Physics I and Center for Materials Research, Justus-Liebig-University Giessen, Giessen, Germany
[2] Faculty of Physics and mar.quest | Marburg Center for Quantum Materials and Sustainable Technologies, Philipps-University Marburg, Marburg, Germany
[3] Department of Physics, Cambridge University, Cambridge, United Kingdom
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Cubic $In_xGa_{1-x}N$ alloys are promising 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 despite never supplying gallium and indium simultaneously.

We discuss the underlying physical phenomena enabling the self-assembled formation of cubic $In_xGa_{1-x}N$/GaN quantum wells using molecular beam epitaxy (MBE) [2]. *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 X-ray diffraction (XRD). At the chosen growth temperature, indium does not incorporate into the underlying c-GaN layer and binary c-InN formation is excluded. 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, 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.

References:

[1] Jentsch, S.A. et al., ACS Appl. Electron. Mater., 7, 1891, (2025)

[2] Zscherp, M.F. et al., Cryst. Growth Des., 25, 3793, (2025)

Cubic InGaN for Red Emission: Improved Phase Stability and Emission Properties by Metal-Modulated Epitaxy

Silas A. Jentsch[1, *], Mario F. Zscherp[1], Aidan F. Campbell[2], Markus Stein[1], Matthew Chia[1,3], Donat J. As[4], Jonas Lähnemann[2], Sangam Chatterjee[1], and Jörg Schörmann[1]
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[2]Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., Berlin, Germany
[3]Department of Physics, Cambridge University, Cambridge, United Kingdom
[4]Department of Physics, Paderborn University, Paderborn, Germany
*E-mail: silas.a.jentsch@materialwiss.uni-giessen.de

Cubic III-nitrides are a promising alternative to conventional wurtzite-based InGaN systems for visible light emission, particularly in the red spectral region, due to the absence of internal polarization fields. We present a systematic study of cubic InGaN layers grown by plasma-assisted molecular beam epitaxy (PAMBE) using two different growth schemes: conventional growth and metal-modulated epitaxy (MME) [1,2]. Three types of structures were investigated, namely bulk layers, multiple quantum wells (MQWs), and single quantum wells (SQWs). MME-grown samples show improved surface morphology and enhanced phase purity, including a complete suppression of hexagonal inclusions. Photoluminescence (PL) measurements confirm red emission from all samples and reveal multiple emission peaks for the quantum well samples. Based on micro-cathodoluminescence mapping, the main emission peak is most likely attributed to carrier recombination in the QW or bulk regions, while the high-energy peak is associated with localized surface features, such as pits. Temperature-dependent PL measurements show different thermal quenching behavior for the two peaks. Power-dependent measurements confirm that all samples exhibit remarkable emission energy stability over nearly two orders of magnitude variation in excitation power. The spectrally-integrated PL intensities recorded at various temperatures demonstrate the robust emission efficiency retaining up to 25% of their low-temperature PL intensity at room temperature. These results demonstrate the potential of MME-grown cubic InGaN for efficient red emission and underline its relevance for future micro-LED applications.

[1] S.A. Jentsch et al.: Appl. Electron. Mater. 7, 1891 (2025).

[2] M. F. Zscherp et al.: Cryst. Growth Des. 25, 3793 (2025).

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Friday, December 5th 2025, 9:40 – 10:40

Schinkelsaal

Nitrides on TiN

9:40-10:00	Kaynar - Epitaxial growth and crystalline phases of $Ti_{1-x}Al_xN$ on Si (111) using cubic TiN and wurtzite AlN buffer layers
10:00-10:20	John - Epitaxial integration of GaN platelets and thin films on metallic TiN using a MBE-MOVPE hybrid approach
10:20-10:40	Dadgar - True vertical GaN diode on TiN-on-Si(111)

Epitaxial growth and crystalline phases of $Ti_{1-x}Al_xN$ on Si (111) using cubic TiN and wurtzite AlN buffer layers

E. Kaynar*, F. Hörich, J. Bläsing, F. Großmann, U. Velpuri, A. Strittmatter, and A. Dadgar

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Gallium nitride (GaN)-based semiconductors offer key advantages over silicon (Si) and silicon carbide (SiC) for high-power and high-breakdown-voltage devices [1]. While lateral HEMTs are commercially available, vertical GaN devices remain under development due to the large lattice and thermal mismatch between GaN and Si, which limits layer thickness and induces cracking [2,3]. Low-temperature epitaxial techniques are therefore essential. Pulsed reactive magnetron sputtering enables high-quality epitaxy below 900 °C and represents a promising approach [4]. Conductive $Ti_{1-x}Al_xN$ alloys are suitable buffer materials for GaN-based vertical devices on Si. Their tunable bandgap, thermal stability, and high conductivity make them strong candidates to replace conventional insulating Al (Ga)N buffers, allowing for backside contacts on substrate and, hence, simplified device fabrication.

In this work, $Ti_{1-x}Al_xN$ layers were epitaxially grown on n-type Si (111) using pulsed reactive magnetron sputtering with TiN and AlN buffer layers. Both buffers were grown in two steps in different plasma: First, an Ar/N_2 plasma is used which suppresses SiN_x formation, then Ar/NH_3 plasma is used to improve surface morphology. This yielded highly crystalline cubic TiN (ω (111) FWHM ≈ 0.3°) with smooth surfaces (RMS ≈ 0.8 nm) and excellent conductivity ($2.2 \times 10^{-7}\ \Omega\cdot$cm). On these optimized buffers, 150–200 nm $Ti_{1-x}Al_xN$ layers were grown. X-ray diffraction confirmed high-quality cubic TiAlN for Al concentrations up to $x \approx 0.4$, where the cubic phase remained stable. As the Al content increased beyond this level ($x \gtrsim 0.4$), a gradual transition toward the wurtzite phase was observed. For AlN-buffered structures, the wurtzite template promoted wurtzite TiAlN at high Al fractions ($x \gtrsim 0.4$), which transformed into the cubic structure with increasing Ti. Throughout this transition, ω-scan FWHM values stayed below 1°, and AFM (5x5 μm^2) showed RMS roughness ≤ 4 nm. Films grown at 800 °C exhibited the lowest RMS values, confirming that higher growth temperatures enhance surface kinetics and promote smoother morphologies.

The ability to control the wurtzite–cubic transition while maintaining high crystallinity and smooth morphology highlights $Ti_{1-x}Al_xN$ as a promising buffer or contact material for vertical GaN-based devices on Si substrates.

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Epitaxial integration of GaN platelets and thin films on metallic TiN using a MBE-MOVPE hybrid approach

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The epitaxy of group III-nitrides directly on metallic substrates is an attractive approach to provide an integrated bottom electrode for miniaturized devices, such as micro light-emitting diodes and bulk acoustic wave resonators. Yet, few metals withstand the harsh growth conditions of nitride epitaxy without reacting with the growing semiconductor. TiN is a refractory transition metal nitride (melting point of 2930 °C), thus providing both high electrical conductivity and thermal stability, but its high interfacial energy with group III-nitrides inhibits the nucleation of two-dimensional layers and instead promotes the formation of nanostructures.

In this work, we first grow self-assembled GaN nanowires on TiN by plasma-assisted molecular beam epitaxy (MBE). Nanowire ensembles of variable density serve as template for epitaxial lateral overgrowth by metal-organic vapor phase epitaxy (MOVPE). While low-density nanowire ensembles lead to the formation of µm-sized GaN platelets, coalesced GaN layers are obtained from high-density ensembles. The TiN film remains intact during growth at temperatures up to 1200 °C, forming a smooth interface with the overgrown GaN revealed by transmission electron microscopy. Current-voltage measurements through highly Si-doped GaN platelets and the underlying metallic TiN film demonstrate ohmic behavior for currents up to 20 mA. Finally, narrow band edge luminescence is observed from cathodoluminescence spectroscopy, demonstrating the high quality of the GaN-on-metal platform.

The monolithic integration of GaN on metallic TiN substrates demonstrated here paves the way for the fabrication of GaN-based vertical devices with innovative architectures.

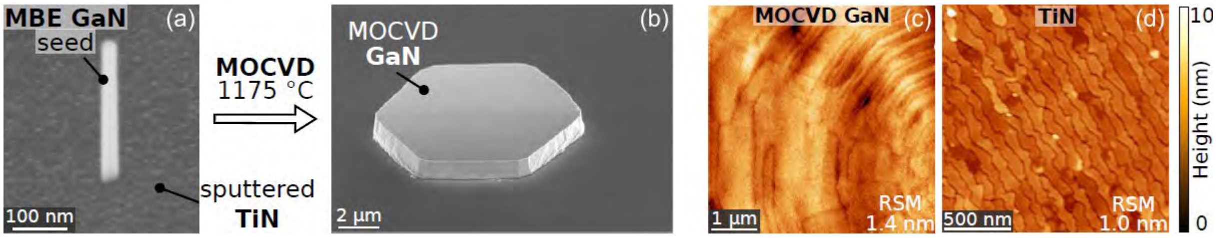

Fig. 1: Birds-eye secondary electron micrographs of (a) an MBE-grown GaN seed nanowire before and (b) a GaN platelet after MOVPE regrowth. Atomic force topographs of (c) a GaN platelet and (d) the TiN surface after regrowth.

True vertical GaN diode on TiN-on-Si(111)

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GaN-on-Si vertical devices are difficult to achieve, as it is required to apply a protective layer on Si during epitaxial growth, which inhibits the melt-back etching reaction of Ga and Si. Commonly insulating AlN is used and therefore vertical devices require either a pseudo-vertical contacting scheme [1], limiting device performance, or local removal of the Si-substrate and Al-rich buffer layers [2]. We present an alternative by applying a cubic and metallic TiN/AlTiN buffer layer followed by AlGaN:Si and a GaN p-n diode. Two approaches were used for TiN/AlTiN buffer layer growth: Either sputtering epitaxy from Ti and Al targets or by MOVPE using $TiCl_4$, TMAl and ammonia. As it is well known ammonia strongly reacts with Cl leading to deposits close to the gas inlet, also in our case. Nevertheless, good quality TiN layers can be grown in MOVPE. The main difficulty in MOVPE was the growth of AlTiN where pre-reactions likely inhibit the growth of Al containing layers. We assume the formation of $AlCl_3$ by pre-reactions of TMAl and $TiCl_4$ inhibiting the growth of ternary AlTiN layers. However, on sputter epitaxial TiN/AlTiN buffer layers we could grow a smooth III-N layer structure with good vertical conductivity. Interestingly during overgrowth of the sputtered buffer layers, the initial XRD diffraction peak of AlTiN disappeared and it is indicated that Ga(Al)TiN has formed instead.

After processing, the 850 nm thin GaN diode demonstrates a breakdown of -20 V, limited by the low layer thickness and the high dislocation density in such a thin layer.

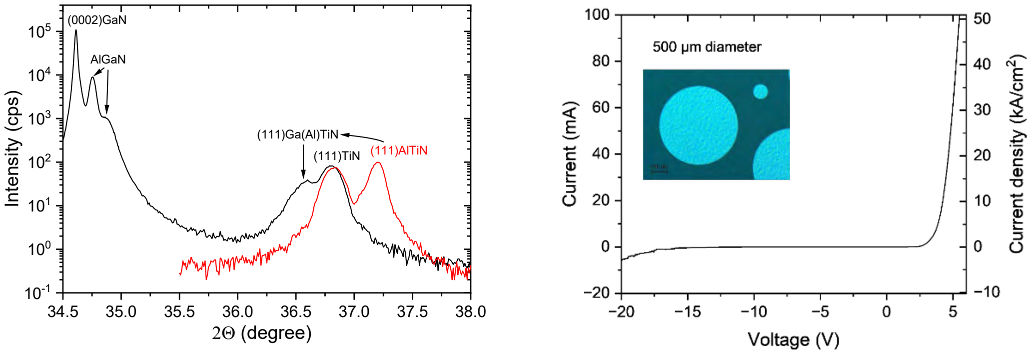

Fig. 1 left: Θ-2Θ diffraction of the sputtered buffer layer (red) and the overgrown buffer (black) showing the transition of AlTiN likely to Ga(Al)TiN. right: I-V characteristic of the grown diode structure when contacted vertically and DIC microscope image of the processed diode.

[1] Y. Zhang, A. Dadgar, and T. Palacios, J. Phys. D: Appl. Phys. **51**, 273001 (2018)

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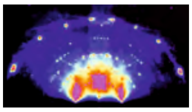

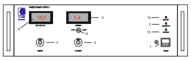

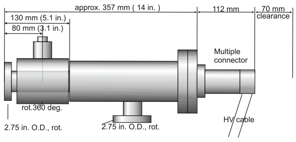

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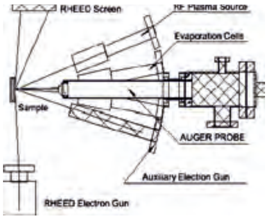

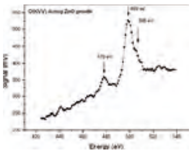

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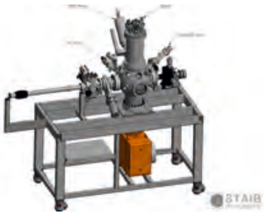

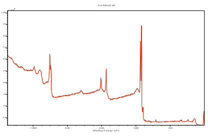

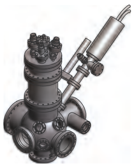

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Friday, December 5th 2025, 11:20 – 12:20

Gartensaal

Sputter Epitaxy and Local Epitaxy

11:20-11:40	Hörich - In-situ measurements in reactive sputter epitaxy
11:40-12:00	Ott - Magnetron Sputter Epitaxy of AlN and GaN on up to 200 mm Substrates
12:00-12:20	Bruckmann - Progress in local epitaxy of GaAs on Si by Laser-assisted MOVPE

In-situ measurements in reactive sputter epitaxy

F. Hörich*, E. Kaynar, R. Borgmann, J. Bläsing, A. Strittmatter, and A. Dadgar
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Monitoring machine parameters in-situ is decisive to ensure stable and repeatable growth processes. With real-time feedback from gas flow, pressure, plasma parameters and temperature, growth of high quality metallic or semiconducting layers can be more accurately tracked and hence more efficiently optimized. Additional valuable information about the plasma is obtainable from spectral footprints of the plasma emissions.

To gather information about the growing layer we installed an optical in-situ monitoring tool (EpiTT by LayTec) to measure surface reflectance at three different wavelengths. This data combined with pyrometric surface temperature measurements is used to evaluate growth rate and evolution of surface roughness for epitaxial growth of nitrides by reactive sputtering.

We optimized AlN sputtering AlN through a 2-step growth approach were AlN is first grown with a nitrogen/argon plasma followed by an ammonia/argon plasma [1]. The ammonia-plasma regime yields an improved surface morphology as confirmed by an increased amplitude of the Fabry-Perot oscillations (FPO) at a reflectance wavelength of 405 nm. Additionally, the growth rate dependence on NH_3 flow and plasma voltage was analyzed based on the FPOs. Growth rates in a range of 200-780 nm/h were measured at 200 W constant plasma power for ammonia flows between 10 and 20 sccm.

For GaN sputtering at a chamber pressure of 5×10^{-3} mbar, the surface roughness turns out to be very sensitive to growth temperature. We find an optimum for the growth temperature of 715 °C (in a temperature range of 690-765 °C) according to the amplitude of the FPOs. At this temperature GaN is partially absorbing the incident light at 405 nm leading to rapidly decaying oscillations. Nevertheless, a constant average reflectance amplitude is in agreement with the low surface roughness rms value of 0.33 nm as measured by atomic force microscopy.

Furthermore, the newly emerging transition metal nitrides like AlScN and AlTiN were investigated using the in-situ metrology system. Again, the growth rate could be monitored and certain plasma conditions could be assigned in-situ to growth instabilities. Special interest is given to phase-change materials such as AlTiN where the phase-change region of composition is accompanied by strong changes of fundamental optical characteristics.

[1] F. Hörich, R. Borgmann, J. Bläsing, G. Schmidt, P. Veit, F. Bertram, and A. Dadgar: *Journal of Crystal Growth* 571, 126250 (2021).

Magnetron Sputter Epitaxy of AlN and GaN on up to 200 mm Substrates

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Group-III nitrides are typically grown using established techniques such as Metal-Organic Chemical Vapor Deposition (MOCVD), which produces high-quality films but relies on high growth temperatures and toxic precursors. Due to these limitations and the rising demand for III-nitride layers, alternative methods have gained interest. Magnetron Sputter Epitaxy (MSE) offers advantages such as improved sustainability, lower costs, easy scalability, and high throughput. In this contribution we present our latest achievements of high-rate III-nitride MSE on a 200 mm platform, using a Double Ring Magnetron (DRM) technology and advanced Ga magnetron cooling (solid Ga maintained at -40°C during deposition), both developed at Fraunhofer FEP, allowing controlled reactive magnetron sputtering at high growth rates up to >1 nm/s [1]. We show that for AlN(0001) on Si(111) the AlN polarity (Al- or N-polar) can be controlled just by the MSE process itself, which is not possible with MOCVD [2]. An in-depth analysis of the grown AlN layers reveals high crystalline quality of XRC-FWHM(00.2/10.1) of 0.5°/1.0° and 0.9°/1.3° for Al- and N-polar, and low roughness (RMS 0.8 nm and 1.2 nm for Al- and N-polar). For sputtered AlN(0001) on Al_2O_3(0001) a post-deposition High-Temperature Anneal (HTA) in face-to-face configuration at 1700°C improved the surface roughness from RMS 1.3 nm to 0.3 nm. Along with the drastic improvement of crystalline quality of XRC-FWHM(00.2/10.1) 0.26°/0.75° to 0.06°/0.28°, the gained film properties are in line with the current state-of-the-art [3,4]. For GaN(0001) on Al_2O_3(0001) we show an excellent crystalline quality of XRC-FWHM(00.2/10.1) of 0.46°/0.67°, as well as a low roughness of RMS 3.7 nm.

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[2] M. Ott *et al.*, *manuscript in preparation* (2025).

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Progress in local epitaxy of GaAs on Si by Laser-assisted MOVPE

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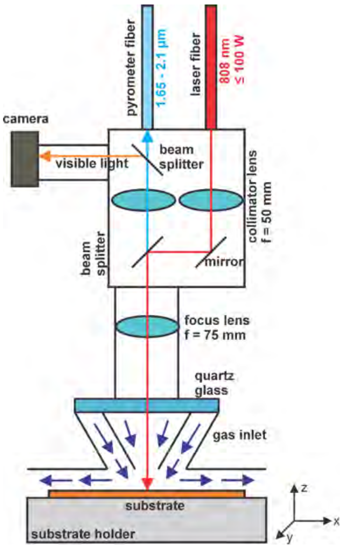
The monolithic integration of group III-V compound semiconductors on silicon is a highly desirable goal as it enables a multitude of advantages in fabrication of complex semiconductor devices compared to hybrid integration approaches. However, due to differences in the fundamental properties of the materials involved, the heteroepitaxial growth generally results in high defect densities in the grown layers. While different approaches are currently being developed to overcome these difficulties, the common focus of these is large-scale production, i. e. the fabrication of the same device structure in all growth areas.

In special cases, however, an additive approach to epitaxial growth can be beneficial, e. g., for applications requiring only a small number of devices or fabrication of different device structures in dedicated areas on the wafer.

The newly developed laser-assisted MOVPE allows for an additive fabrication of compound semiconductor devices using a high-power laser for local substrate heating. [1] By adjusting the laser spot diameter, the desired growth diameter can be selected. While the current experimental setup is limited to a gaussian intensity profile resulting in an inhomogeneous temperature distribution, the average temperature within the growth area is measured with a pyrometer. In addition to the inherent advantages of additive manufacturing, LA-MOVPE also enables device fabrication without exceeding the thermal budget of devices already present on the wafer.



LA-MOVPE was used for growth of GaAs islands on exactly oriented Si(100) and on Si(100) with a 4.5° offcut. Similar to conventional MOVPE growth on Si a two-step approach consisting of a low-temperature nucleation layer and a high-temperature buffer layer was used. Experiments for the optimization of the growth parameters were conducted where the primary focus was on the nucleation growth. Subsequent characterization reveals a qualitative dependence of the RMS value determined by AFM and FWHM by XRD on the nucleation thickness and temperature similar to that known from planar MOVPE. In addition SEM measurements were used to investigate the structure of grown nucleation layers.

Patterned substrates for restricting growth to the central part of the heated area can lead to a further improvement in crystalline quality.

[1] M. Trippel et al.: Rev. Sci. Instrum. 93, 113904 (2022)

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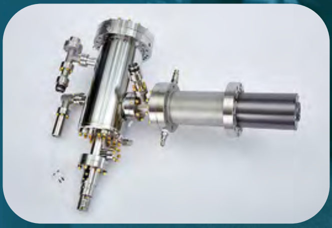

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Nitrides : Growth & Characterization

11:20-11:40	Bertram - Nanoscopic Insights into the Structural and Optical Properties of the Active Region of Far-UVC-LEDs: Impact of Composition Gradient in Polarization Doping
11:40-12:00	Abbas - Bravais class like Hexagons based micro-/nano UV optical cavity for next-generation opto-electronics
12:00-12:20	Koch - Following Charge Carrier Transport in Freestanding Core–Shell GaN Nanowires on n-Si(111) Substrates

Nanoscopic Insights into the Structural and Optical Properties of the Active Region of Far-UVC-LEDs:

Impact of Composition Gradient in Polarization Doping

F. Bertram,[1,*] , E. Bäker,[1] N. Dreyer,[1] G. Schmidt,[1] J. Christen,[1] T. Kolbe,[2]
S. Hagedorn,[2] H.K. Cho,[2] J. Rass,[2] S. Einfeldt,[2] and M. Weyers[2]
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Far ultraviolet AlGaN-based LEDs emitting below 250 nm have attracted much attention for their wide rang of applications. In the UV spectral range, especially in the far-UVC, low hole injection efficiency caused by a combination of a high Mg activation energy and limited hole mobility in the p-AlGaN layer, as well as the need to control non-radiative recombination channels, poses major challenges. The use of a polarization doping is an effective solution to achieve a reasonable hole injection into the active region of deep-UVC LEDs.

In this study far-UVC LEDs with different AlGaN composition gradients used for polarization doping are compared. The LEDs were grown by MOVPE on double growth and double annealed AlN/sapphire templates with a constant thickness of the polarization doped layer but different composition gradients. The Al mole fraction has been changed during growth linearly from the start value 1 to the end values of 0.8, 0.75, 0.5 and 0.2. A direct one-by-one correlation of the optical properties with the real structure of the deep-UV-LED is presented using low temperature cathodoluminescence spectroscopy (CL) directly performed in a scanning transmission electron microscope (STEM). This enables the analysis of local defect density, composition homogeneity—particularly the in-plane Al distribution in the AlGaN layer—strain distribution, and impurity incorporation at the nanometer scale.

A cross-sectional CL linescan along the active region reveals the characteristic emission of the individual layers of the sample with the Al-gradient reaching x_{AL} =0.5: the n-$Al_{0.88}Ga_{0.12}N$ buffer exhibits an intense emission at 224 nm, whereas the UV-MQW emits at a wavelength of λ = 230 nm. The emission of the subsequent following AlGaN gradient layer shows contributions between 240 - 260 nm.

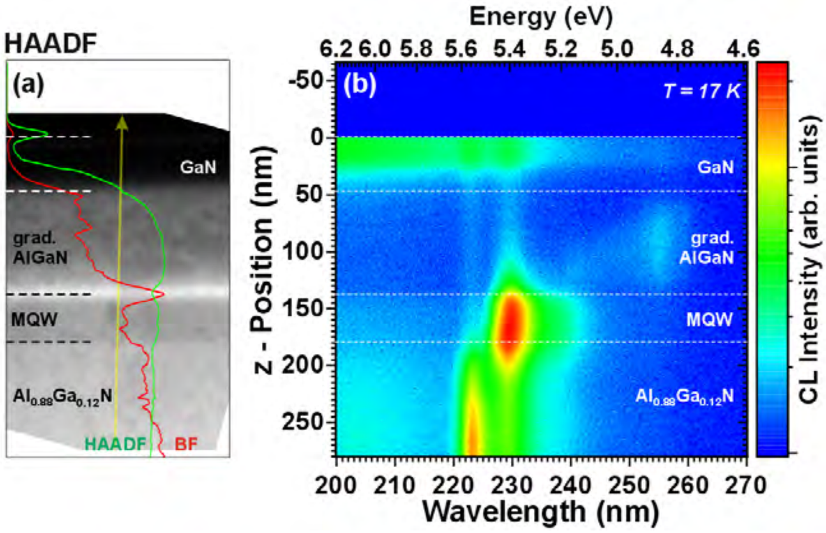

Fig. 1: STEM image (left) and CL linescan (right) at T = 17 K across MQW and polarization doped AlGaN gradient layer.

Bravais class like Hexagons based micro-/nano UV optical cavity for next-generation opto-electronics

ARWA SAUD ABBAS1*
ABDULLAH JALALAH, FAHAD ALBAQAM, ABDLRHMAN HIAZAA, MOHAMMED ALKHAMISAH, ALI ZAED ALANZI, FADHL S. ALFADHL
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This research employs InGaN/GaN epitaxial heterostructures designed for operation at a wavelength of approximately 405 nm. It investigates hexagonal optical micro- and nanocavities, categorized analogously to the Bravais lattice system, whose hexagonal geometry and resonant properties based on 405 nm heterostructures facilitate light localization within ultra-small volumes [1, 2]. The study details the fabrication of hexagonal optical cavities incorporating $In_xGa_{1-x}N$ ($x = 11.5\%$) quantum wells (QWs) with undoped GaN quantum barriers (QBs), followed by optical characterization through photo-pumping. A top-down fabrication approach was adopted to realize the hexagonal optical structures. Each cavity consists of ternary $In_{0.115}Ga_{0.885}N$ double quantum wells (2 QWs) with a well thickness of 2.75 nm and 5 nm GaN quantum barriers, where the emission wavelength can be tuned by varying the indium composition. The process yields well-defined hexagonal devices, as illustrated in Figure 1(a–c). The photoluminescence (PL) spectra shown in Figure 1(d), measured at room temperature under 370 nm laser excitation, confirm the targeted emission wavelength of approximately 404 nm.

The fund is by the King Abdulaziz City for Science and Technology (KACST) through utilizing KACST cleanroom and KACST facilities. Thanks for ORBIT-KACST team for discussion regarding KACST cleanroom standard operation.

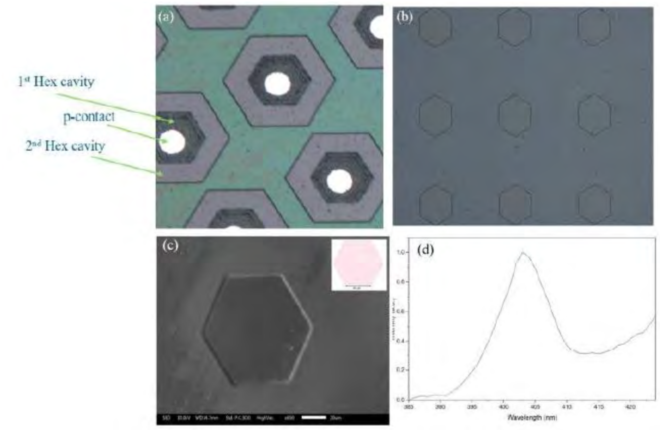

Figure 1. Hex optical cavities fabrication, (a,b) optical microscope of the resulting mesas for photo-pumping were 48×48 μm2, (c) SEM image, (d) Photoluminescence (PL) spectra of the fabricated hex structure, and PL at room temperature using the laser excitation source of 370 nm.

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Following Charge Carrier Transport in Freestanding Core–Shell GaN Nanowires on n-Si(111) Substrates

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Precisely defined heterojunctions within nanostructured devices are essential for advancing nanoscale systems with superior electrical performance. To fully harness these capabilities, it is crucial to examine their electrical and structural behavior with high spatial resolution to gain key insights into their functional mechanisms [1-3].

In this context, the present study provides a thorough analysis of charge carrier transport in freestanding core-shell GaN nanowires (NWs) grown on pre-structured n-type Si(111) substrates [4]. The aim of this research is to spatially resolve and thoroughly characterize the transport pathways of charge carriers within the NWs and across their critical interfaces. The core-shell GaN NWs were epitaxially grown via state-of-the-art polarity- and site-controlled growth by metal-organic vapor phase epitaxy, with a site-dependent AlN interlayer [5]. Advanced electrical characterization techniques, including multi-tip scanning tunnelling microscopy and electron beam-induced current mapping, were employed to probe local transport phenomena with high precision. Clear differences in the *I-V* characteristics were observed when contacting different NW facets. Scanning transmission electron microscopy (STEM) imaging further revealed that no direct contact exists between the shell and the core. Consequently, the current transport can be described by three serially connected diodes corresponding to the junctions between (1) shell-to-shell, (2) shell-to-core, and (3) NW-to-substrate. The results elucidate unique transport mechanisms governed by the interplay between core-shell geometry and interfacial states, thereby advancing the fundamental understanding of charge carrier dynamics in III-N nanostructures.

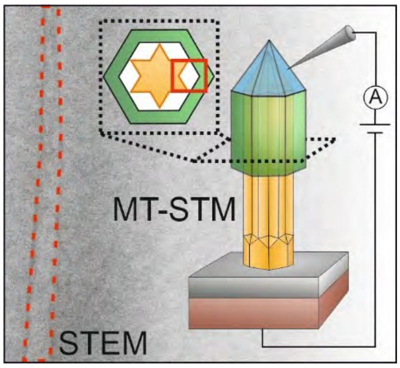

Fig. 1: Schematic illustration of a core-shell GaN NW with STEM background image [4].

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[4] J. Koch and P. Häuser *et al.*, ACS Appl. Electron. Mater. 7, 8, 3469 (2025).
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