Leibniz
Ferdinand
Braun
Institut

frequent

Materials technology – where device fabrication starts

- *controlling light* – GaAs growth processes for laser diodes
- *coping with the challenges* – growth processes for nitride-based devices
- *looking closely* – comprehensive material analysis down to the nanoscale

Materials technology – where device fabrication starts

Epitaxial layers are the starting point for device fabrication and determine their properties to a large extent. FBH's Materials Technology Department supplies heterostructures for device development at the institute itself, but also supports device manufacturing of partners and clients with their customer-specific layer designs. Al(Ga)N layers are grown on silicon carbide for nitride transistors, on sapphire for UV LEDs and on GaN for blue-violet laser diodes. AlGa(In)As and AlGaInP are grown on gallium arsenide primarily for devices emitting light from the red (630 nm) up to the near-infrared (1180 nm) wavelength range.

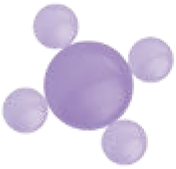
To efficiently supply the vast range of different device structures for numerous diverse applications studied at FBH, state-of-the-art multiwafer MOVPE (metalorganic vapor phase epitaxy) production reactors are employed. Tools assessing the properties of the individual layers like thickness or wafer bow, which results from lattice mismatch, ensure optimal device development already during growth. This minimizes the time for switching between different layer designs and ensures reproducibility even over many years. In some cases, such as VCSELs, the layer thicknesses must be adjusted to better than 1 % in order to hit the targeted emission wavelength. This cannot reasonably be achieved without *in situ* control. During the growth of III-nitrides, strain relaxation needs to be managed and controlled additionally, making *in situ* assessment of wafer bow and surface roughening even more important than for arsenides.

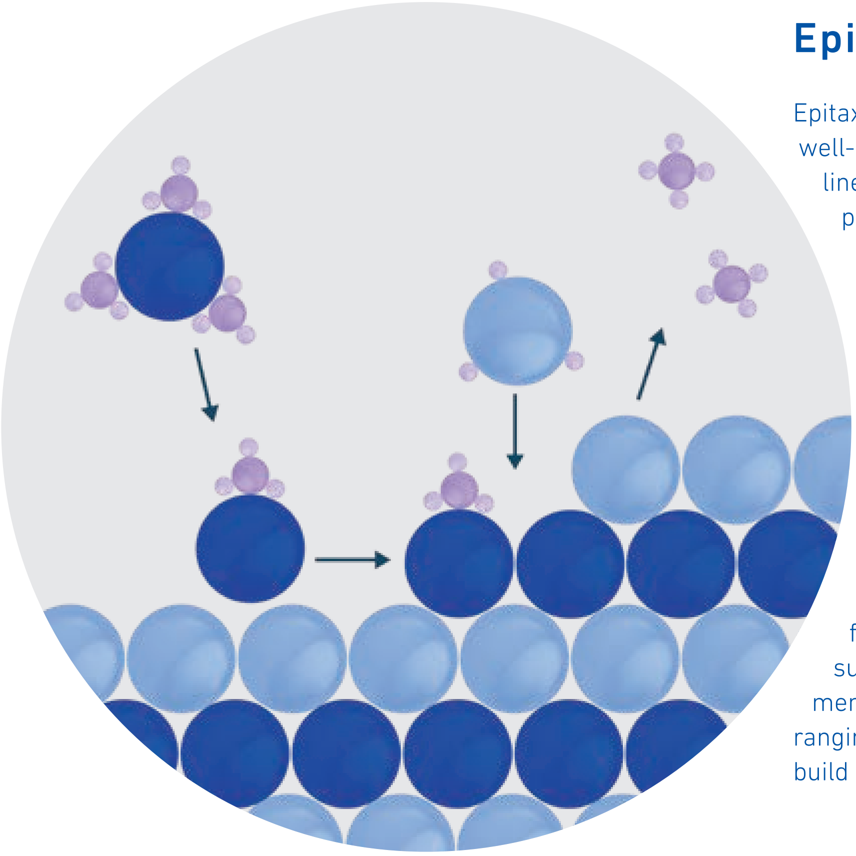
High-quality devices thanks to comprehensive analysis

Assessing the properties of the grown layer structure is essential in the development of growth processes – making sure that the delivered wafers meet the device specifications. FBH therefore investigates the following properties in-depth:

- crystalline – by X-ray diffraction and TEM
- morphological – by optical, electron, and atomic force microscopy
- electrical – by Hall-effect measurements and C-V profiling
- optical – by transmission, electro-, photo-, and cathodoluminescence

These analytical methods also help to understand failure mechanisms of devices. Finding out whether the root causes for failures are related to the layer structure itself, to processing steps or to device mounting is essential to finally yield devices with top performance and high reliability. These capabilities in materials analysis are also offered to partners and customers.





Epitaxy

Epitaxy is the growth of crystalline layers with well-defined orientation with respect to a crystalline substrate (wafer). Deposition has to be performed elaborately, atomic layer after atomic layer, to achieve layers with smooth surfaces and uniform thickness, thus yielding the desired device properties. At FBH, alloys made from the group III atoms aluminum, gallium, and indium and the group V atoms arsenic and phosphorus (for growth on gallium arsenide) or nitrogen (for growth of nitrides) are grown by MOVPE. The group III atoms are supplied as metalorganic molecules like trimethylgallium, group V ones as hydrides like ammonia. These gases react, forming semiconductor layers on the heated substrates (500 °C – 1200 °C). Precise adjustment of the composition and layer thicknesses ranging from 1 nm to several µm is necessary to build the desired layer structure.

Editorial

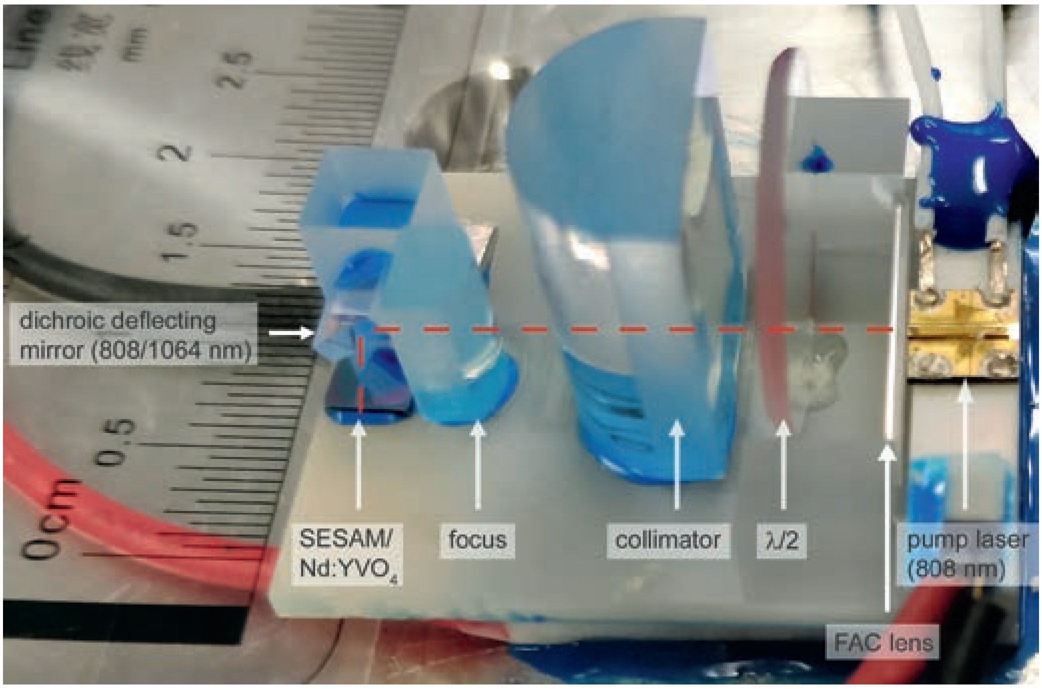
Experience has shown us that each completed product can only be as good as the individual steps taken to produce it. That's why we carefully design, monitor and adjust every single process step, starting with epitaxial layer growth to yield the targeted device properties. Our institute uses state-of-the-art equipment in a high-performance cleanroom environment – for arsenide- as well as nitride-based devices, accompanied by comprehensive material analysis. We have compiled an overview on our extensive activities in materials technology for III-V semiconductors.

I wish you an inspiring reading,

Günther Tränkle

SESAMs for ultrashort laser pulses with high peak power

A saturable semiconductor absorber mirror (SESAM) consists of a highly reflective Bragg mirror structure and a layer changing from absorbing to transparent with increasing pump light intensity. Such devices are key to generate ultrashort laser pulses in the fs to ten ps range by passive mode locking. Over the last two decades, the FBH has been developing tailor-made SESAMs for leading laser manufacturers, utilized in systems for eye surgery as well as for cutting of hard materials like metal or glass. Compact and cost-efficient laser systems with sub-ns pulses that offer high peak power and low repetition rates can also be realized by Q-switching. The FBH has developed SESAMs, which consist of an AlAs/GaAs distributed Bragg reflector designed for 1064 nm center wavelength, an InGaAs multi quantum well absorber section, and a coating based on SiN_x and SiO_2. Comparably long carrier relaxation times of about 600 ps were obtained – in contrast, only several ps are needed for mode locking – to achieve sufficient inversion in the laser crystal, and therefore high peak power. Such a SESAM was bonded to a $Nd{:}YVO_4$ laser crystal and incorporated into a seeder module. Diode-pumped at 808 nm, about 185 ps short light pulses at 1064 nm with 300 nJ pulse energy were generated.



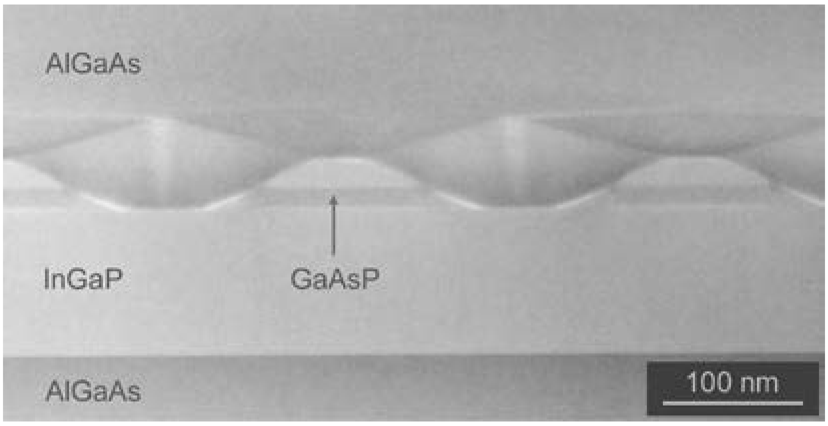
Microchip laser module developed by partners based on FBH's SESAMs.

Controlling light – sophisticated growth processes on GaAs for laser diodes with tailored properties

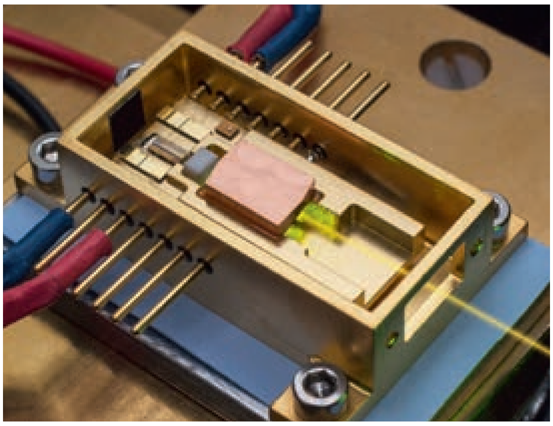
FBH is one of the internationally leading institutes for the precise control and manipulation of laser light. For its partners in industry and research, it develops III-V semiconductor lasers for a great variety of applications, which consequently requires numerous different gallium arsenide (GaAs)-based heterostructures. Devices in the near-infrared (NIR) spectral region from 730 nm up to 1180 nm have AlGaAs waveguides with GaAsP, GaInAs or AlGaInAs light-emitting quantum wells (QWs). For the red spectral region from 630 nm to 690 nm, GaInP QWs embedded in AlGaInP waveguides are used. GaInAsP QWs are explored to close the gap between 690 nm and 730 nm. Over this whole wavelength range, FBH offers state-of-the-art performance of broad area and narrow ridge-waveguide laser diodes.

Depending on the application, not only the wavelength but also doping and composition profiles are optimized. This aims at tailoring, for example, the vertical emission profile or coping with the high carrier densities in pulsed laser diodes used in applications like LiDAR. This results in a large number of different growth recipes even for very similar wavelengths.

In the long wavelength range beyond 1100 nm, growth of heavily strained InGaAs QWs without generating crystal defects is a major challenge to be mastered. In addition to strain compensation by GaAsP, the FBH has also optimized QW thickness and growth conditions to obtain devices with both high output power and high reliability.



Buried DFB grating in NIR laser diode.



Yellow-emitting laser system based on frequency doubling of a 1180 nm InGaAs laser diode.

Meeting the specifications: *in situ* monitoring, aligned processes, and many years of comprehensive experience

AlGaAs waveguides have nearly the same lattice constant as the GaAs substrate. The one of AlGaInP, however, critically depends on the In content, which is, to some extent, affected by the layers previously grown in the reactor. Thus, growth recipes have to be adapted to account for this. To avoid time-consuming and expensive calibration runs, the transient of the wafer curvature is evaluated during the growth runs to adjust the composition especially in the critical region around the QWs. Only this step allows reproducibility of the resulting layer properties. Evaluating oscillations in the reflectivity at specific wavelengths during the growth of individual layers helps to keep track of growth rates across the many different compositions and layer recipes that are needed.

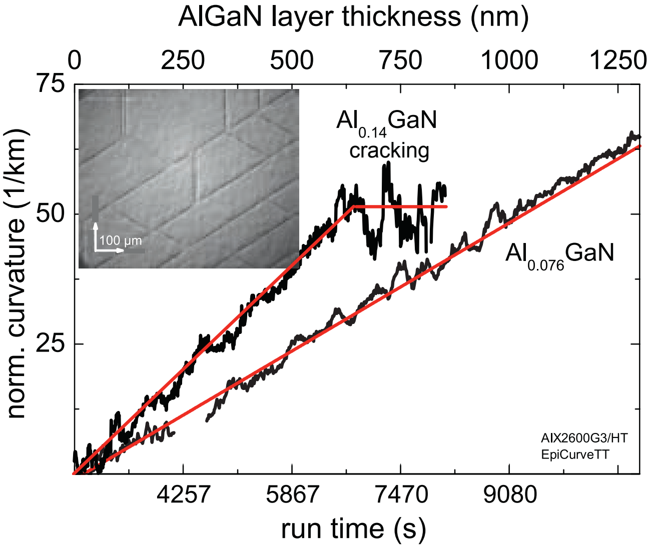
DFB or DBR lasers with buried gratings or photonic-integrated circuits which combine, for example, active laser regions with passive modulators, require regrowth over patterned surfaces. Especially for Al-containing layers, the removal of oxides without damaging the surface pattern is a challenge which can only be mastered by jointly developing the patterning process and the subsequent regrowth process including oxide removal by *in situ* etching in the MOVPE reactor. Such processes are available for the whole NIR spectral region, enabling applications which need tunable devices with narrow spectral linewidth, for example.

The GaAs-based epitaxial growth capabilities are also leveraged to develop vertical devices like SESAMs (see p. 3) and VCSELs. For vertical-cavity surface-emitting lasers (VCSEL) in particular, the layer thickness must be strictly controlled – 1 nm thickness deviation of the cavity results in around 1 nm wavelength divergence. Here, determination of the growth rate obtained in the first layers of Bragg mirrors is used to correct the cavity thickness to its target value.

Using its vast knowledge in this field, FBH supplies wafers for laser diodes to external customers and develops device structures and growth processes for industrial partners.

Coping with the challenges – growth processes for nitride-based devices

Growth of III-nitrides is dominantly performed on a foreign substrate with divergent lattice constant. It starts with islands that merge and finally form a smooth layer, which is then used as basis for device structures. This process leads to a high number of dislocations which decreases during further growth, resulting in a change of the average lattice constant and strain in the growing layers. Even on AlN or GaN substrates the large lattice mismatch results in strain; dislocations occur when growing AlGaN. The FBH has implemented comprehensive measures to manage such strain and thus avoid cracking. Monitoring the wafer curvature is an indispensable tool for this which is extensively used at FBH.



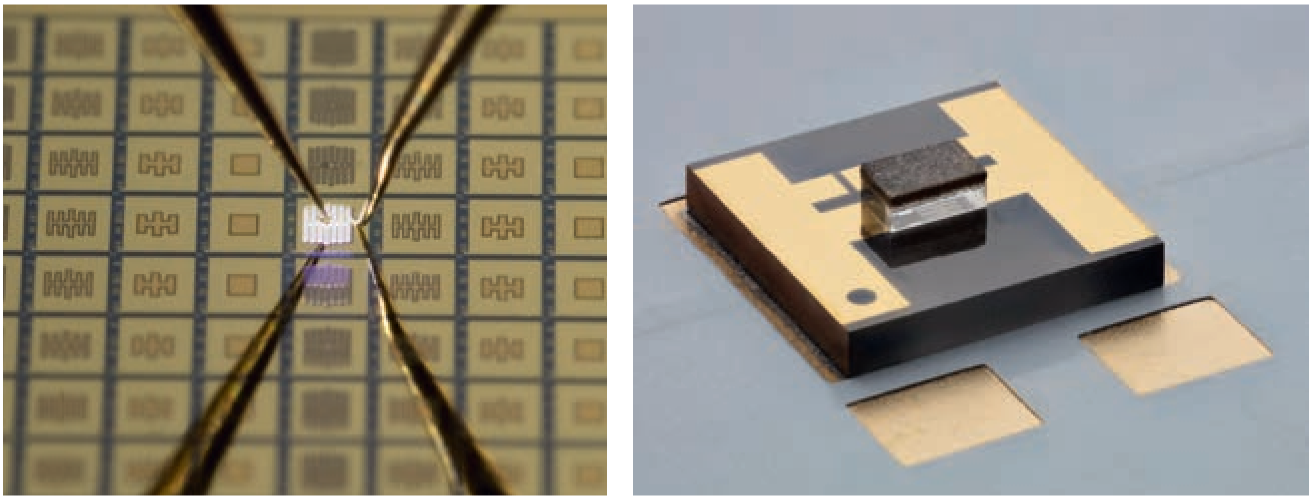
Curvature and strain relaxation in AlGaN layers on GaN.

Heterostructures for electronic devices

GaN and AlN structures for lateral field-effect transistors (FETs) are grown on semi-insulating 4" SiC substrates. The design of the insulating buffer, but especially that of the $Al_xGa_{1-x}N$ barrier layer – a specific combination of thickness and Al content x – is dictated by device requirements such as breakthrough voltage and maximum operation frequency. Layers for vertical devices like vertical GaN trench metal-insulator-semiconductor FETs (MISFETs) and FinFETs are grown on conductive 4" SiC and 2" GaN substrates. Adjusting the required low n-doping level in the GaN drift region is particularly challenging here. In addition to FBH's own demands, wafers are also supplied to industrial partners for their device developments.

Nitride optoelectronics

Heterostructures for violet-blue laser diodes are grown on GaN substrates for the in-house development of narrow ridge-waveguide lasers and DFB lasers with high-order surface gratings. Currently, the transition from a single-wafer reactor to efficient multi-wafer growth is under way. The biggest effort in the field of nitride devices is devoted to UV LED development. For these devices, the AlN buffer layer on transparent sapphire substrates determines the final LED performance to a large extent. A low dislocation density (TDD) is key to high efficiency. Therefore, patterning of the sapphire/AlN interface is used to reduce the TDD and at the same time to enhance the efficiency of light extraction. However, the sapphire substrate is modified when MOVPE growth of AlN at high temperatures starts, resulting in insufficient reproducibility of the grown AlN layer properties. In order to improve yield and reduce effort, sputtered AlN layers are explored, since no chemical attack on the sapphire is possible in this process. The poor crystal quality of such sputtered layers can be substantially improved by treatment at temperatures around 1700 °C before MOVPE growth of the device heterostructures in a 6 x 2" reactor. To achieve optimum device performance, the FBH considers and thoroughly monitors all critical aspects: In addition to a low TDD and a smooth surface, the strain state of the AlN layers is important and routinely controlled during device layer growth. It must also be taken into account that UVB and UVC LEDs require different templates.



UV LED during on-wafer measurement and as device mounted on heat sink.

Looking closely – comprehensive material analysis down to the nanoscale

Characterizing structural, electrical and optical properties of semiconductors is an integral part in the development and optimization of growth processes of device heterostructures and in quality assurance. The used methods also help analyzing device processing steps like the formation of ohmic contacts and pinpointing sources for device degradation. The FBH has extensive experience in developing and applying sophisticated analysis methods used for both in-house developments and services to customers.

Quality assurance

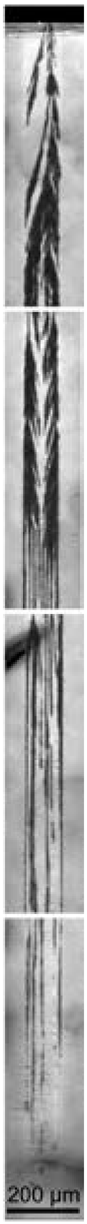
Non-destructive analysis is essential to assess the layer quality. This analysis includes control of the layer composition by high resolution X-ray diffraction, the surface morphology by light and atomic force microscopy, the emission of optical devices by electroluminescence or photoluminescence as well as sheet resistance mapping for electronic devices. Mapping of the spectral reflectance is additionally applied for VCSELs and SESAMs. Data of this post-growth analysis with spatial resolution on the mm-scale are then correlated to data obtained already during growth to verify reproducible growth with target layer parameters.

Process development

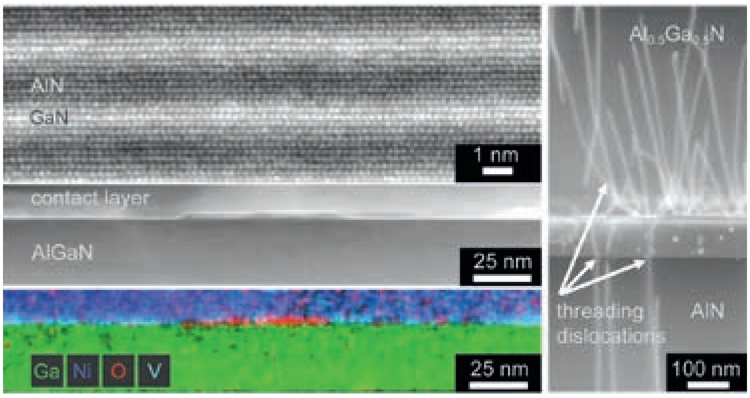
Destructive characterization techniques have to be employed additionally during growth process development. Hall effect measurements and electrochemical C-V profiling are used to adjust the desired doping levels and profiles. Photoluminescence at low temperature yields information on impurity content and defects that cause emission inside the band gap. Also, the homogeneity of composition and thickness of the thin layers (quantum wells), which generate the emission in LEDs and laser diodes, is assessed with this method. For the growth of III-nitride layers on foreign substrates with high lattice mismatch, for example for UVB LEDs, it is necessary to study formation of dislocations, their movement and annihilation. Roughening of interfaces also needs to be understood and mastered. This requires characterization with resolution on the nm- and partly even atomic scale, applying measurement techniques like scanning (SEM) and transmission electron microscopy (TEM) combined with composition sensitive spectroscopy techniques (e.g. EDX, EELS) as well as cathodoluminescence (CL).

Approaches for device improvement and understanding failure mechanisms

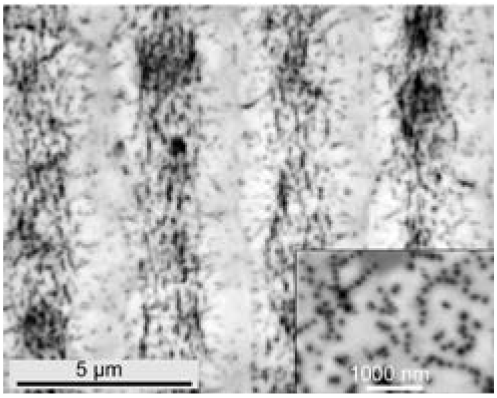
Electron microscopy techniques allow to study, for example, the formation of surface steps, distribution of crystal defects and to visualize compositional inhomogeneity in different device parts. Diffusion of contact metals or damage by ion etching is analyzed to optimize device processing. Very thin layers or lamellae need to be prepared for this by mechanical polishing and ion milling. The capabilities in material analytics are also used for failure analysis of laser diodes and transistors. To access the region of interest metal contacts, substrate and parts of the epitaxially grown active device structure have to be removed. CL analysis can then reveal areas which do not emit light anymore. SEM or TEM allow identifying mechanical damages like cracks, and EDX reveals compositional changes accompanying the degradation processes. These results are the feedback to improve epitaxial growth, device layout and processing and also the mounting of devices to heat sinks or circuit boards.



CL image revealing defect lines along a broad area laser with ▶ origin at the facet.



STEM images of UV LED details: high resolution of AlN/GaN short period superlattice for strain engineering (top left), defect formation in AlGaN on AlN (right); n-ohmic contact: semiconductor-metal interface (middle) with corresponding element distribution (bottom).



Dark spots in cathodoluminescence map show the distribution of dislocations at the surface of a UV LED on patterned sapphire substrate. Magnified inset: area with a dark spot density of 1.6 x 10^9 cm^{-2}.

Growth as a life topic – on Markus Weyers' 60th birthday

Layer by layer – this is most certainly what Markus Weyers has always pursued during his career as with an impressive track record. After starting his career as PhD student at RWTH Aachen University in 1986, he worked as a postdoc researcher at NTT Basic Research Laboratories in Japan. He has been head of FBH's Materials Technology Department since 1992 and was additionally appointed associate professor at Technische Universität Berlin in 2014. Definitely, his know-how covers a broad spectrum of R&D in the field of epitaxial growth, from growth studies to tailored growth processes for devices. These range from laser diodes including VCSEL as well as SESAMs, UV LEDs, photodetectors, AlN- and GaN-based transistors and GaAs-HBTs. Markus Weyers has authored and co-authored more than 500 publications, is holding more than ten patents, and worked as associate editor and as reviewer for journals and research funding organizations. Not only his scientific achievements are remarkable, but also his merits in the field of technology transfer: Markus Weyers has established Three-Five Epitaxial Services AG in 1999 as managing director. The company produced semiconductor layer structures as an epiwafer foundry and was integrated into JENOPTIK's in-house wafer production in 2008. He also co-founded LayTec, a manufacturer for *in situ* metrology equipment to monitor layer deposition, and was later chairman of the company's supervisory board for seven years. We are sure that Markus Weyers will continue to follow his "growth" path with full commitment and energy. We thank him for his many years of dedicated service to the Ferdinand-Braun-Institut and look forward to the coming productive years.

Upcoming conferences

ICULTA
2021

April 18 – 21, 2021 – for the second time, ICULTA 2021 will bring together UV LED experts from science and industry in Berlin. The international conference covers the whole value chain, highlighting the state-of-the-art in UV LED technology up to their application in industry and research. 'Advanced UV for Life' – the consortium's office is located at FBH – and the 'International Ultraviolet Association' jointly organize the event.
www.iculta.com

27th INTERNATIONAL
SEMICONDUCTOR LASER CONFERENCE
ISLC2021

October 10 – 14, 2021 – the FBH is also organizing the 27th International Semiconductor Laser Conference in Potsdam with Paul Crump as General Chair. ISLC2021 is dedicated to latest developments in semiconductor lasers, amplifiers and LEDs.
www.islc2021.org

Please check the conference websites for up-to-date information on changes that may occur due to the COVID-19 pandemic.

The Ferdinand-Braun-Institut, Leibniz-Institut fuer Hoechstfrequenztechnik (FBH) researches electronic and optical components, modules and systems based on compound semiconductors.

These devices are key enablers that address the needs of today's society in fields like communications, energy, health, and mobility. Specifically, FBH develops light sources from the visible to the ultra-violet spectral range: high-power diode lasers with excellent beam quality, UV light sources, and hybrid laser modules. Applications range from medical technology, high-precision metrology and sensors to optical communications in space and integrated quantum technology. In the field of microwaves, FBH develops high-efficiency multi-functional power amplifiers and millimeter wave frontends targeting energy-efficient mobile communications, industrial sensing and imaging, as well as car safety systems. In addition, the institute fabricates laser drivers and compact atmospheric microwave plasma sources operating with energy-efficient low-voltage drivers for use in a variety of applications.

The FBH is a center of competence for III-V compound semiconductors and has a strong international reputation. FBH competence covers the full range of capabilities, from design through fabrication to device characterization. Within Research Fab Microelectronics Germany (Forschungsfabrik Mikroelektronik Deutschland), it joins forces with 12 other German research institutes, thus offering the complete micro and nanoelectronics value chain as a one-stop-shop.

In close cooperation with industry, FBH's research results lead to cutting-edge products. The institute also successfully turns innovative product ideas into spin-off companies. With its Prototype Engineering Lab, the institute strengthens its cooperation with customers in industry by turning excellent research results into market-oriented products, processes, and services.

The institute offers its international customer base complete solutions and know-how as a one-stop agency – from design to ready-to-use modules and prototypes. Overall, working in strategic partnerships with industry, FBH ensures Germany's technological excellence in microwave and optoelectronic research.

Imprint

Publisher:
Ferdinand-Braun-Institut,
Leibniz-Institut fuer
Hoechstfrequenztechnik
Gustav-Kirchhoff-Str. 4
12489 Berlin, Germany
Phone +49.30.6392-2626
https://www.fbh-berlin.de/en/frequent

Editor: Petra Immerz

Layout: telegrafik berlin

Images:
cover: small image left (B. Schurian),
others (FBH)
Katja Bilo: pp. 3 top, 7
Petra Immerz: p. 2
André Marianovich: p. 3 botton
Bernhard Schurian: pp. 4 right,
5 bottom left & right
Christoph Ruß: p. 8
further images: FBH

frequent 13 | October 2020