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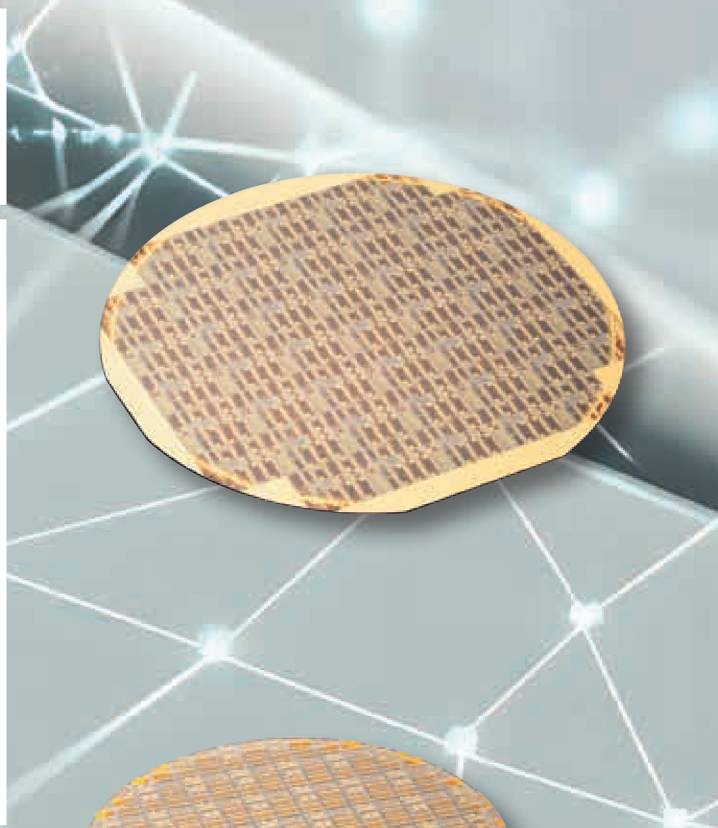
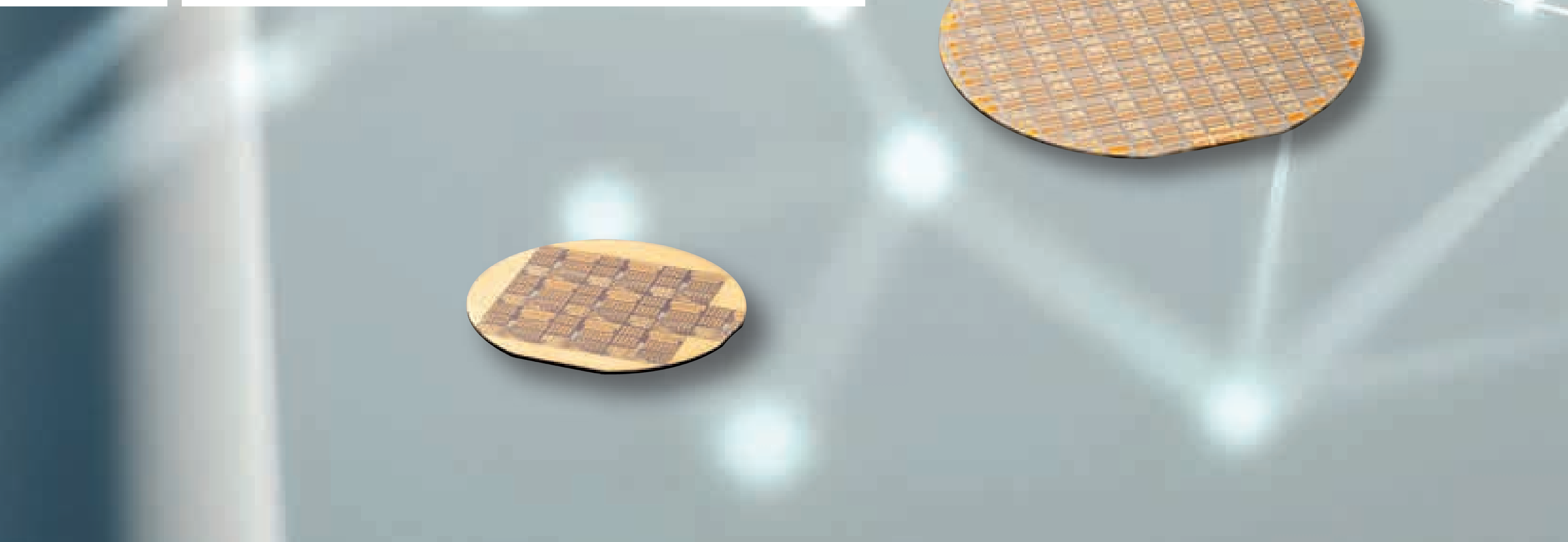
High-performance power-electronic devices based on ultrawide-bandgap semiconductors

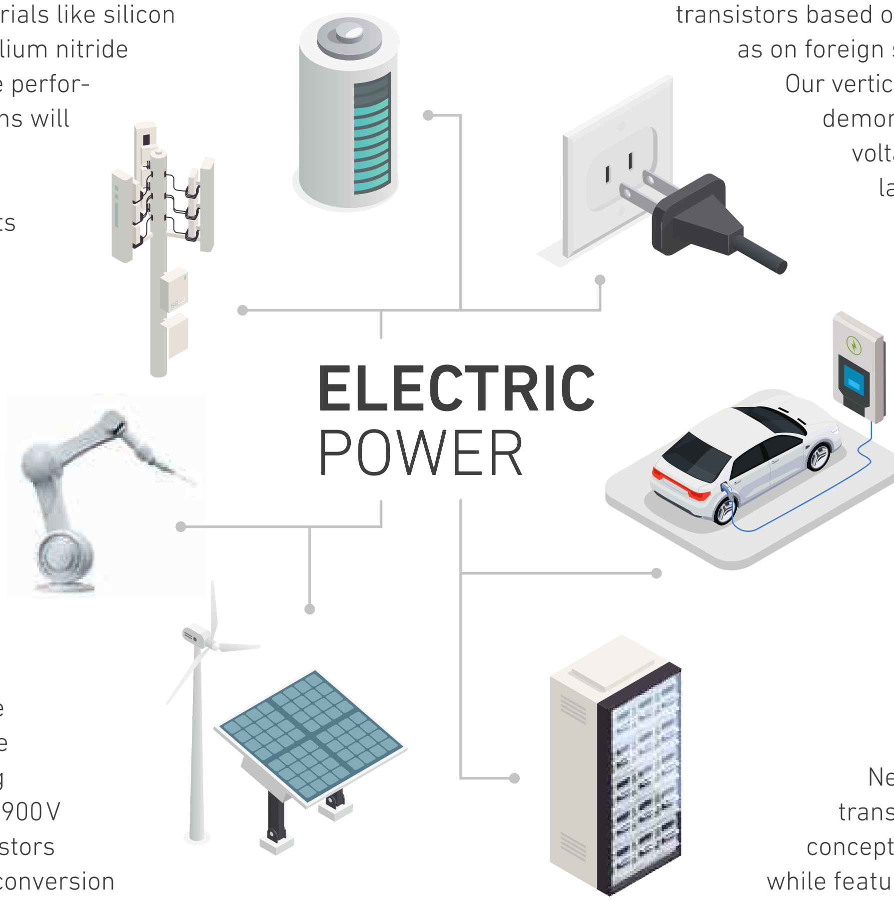


- AlN – devices for fast power switching
- Ga_2O_3 – novel material for high voltages
- GaN – vertical devices for high power



Wide- and ultrawide-bandgap materials for efficient next-generation power electronics

Power converters play a crucial role in enabling efficient energy conversion and management across industries such as renewable energy, electric vehicles, and smart grids. For these demanding applications, they must deliver even higher efficiency, increased power density, and enhanced thermal management, while incorporating advanced semiconductor materials like silicon carbide (SiC) and gallium nitride (GaN) to boost device performance. Future designs will prioritize scalability, high-voltage performance, and also costs to address the growing electrification in the context of clean energy and digitalization.



Already commercialized SiC-based power transistors feature a vertical chip design with the low-voltage and high-voltage terminals separated at the top and bottom of the chip. Typical blocking voltages range from 900 V to 1700 V, with transistors designed for power conversion > 1 kW. Today's GaN transistors are based on a lateral design, with all three terminals on the top side of the chip. Blocking voltages typically range from 48 V to 700 V. They feature an extremely low gate charge with minimal switching losses for highest efficiencies at even higher power densities. GaN-based converter applications are typically < 10 kW.

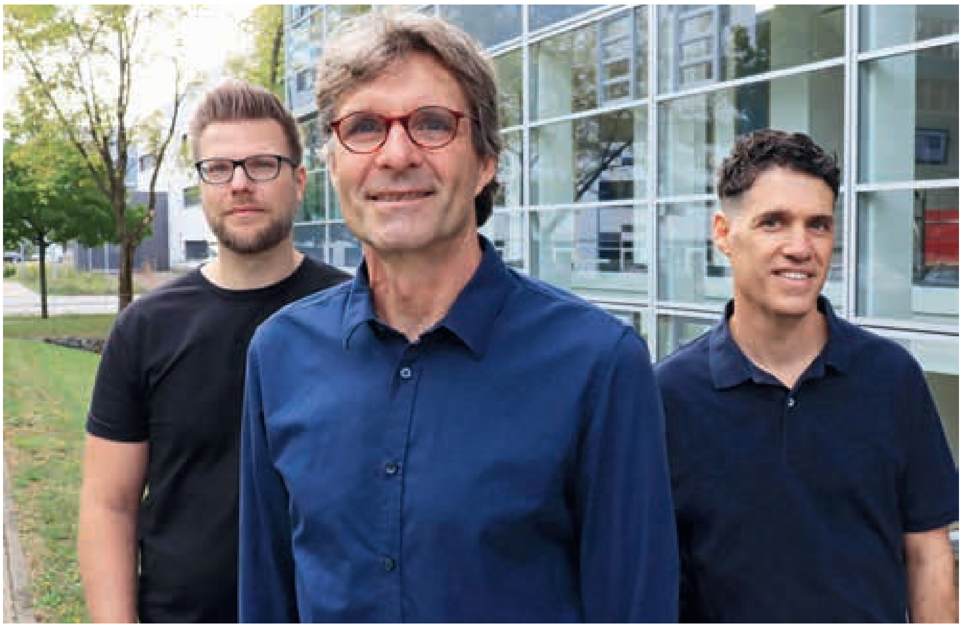
New device technologies for next-generation power switches

The success of SiC- and GaN-based devices motivates further improvements in power switching transistors. Advancements can either be achieved by adopting new device architectures using the now-established wide-bandgap materials or by introducing new semiconductor materials with even higher bandgaps. These are known as ultrawide-bandgap materials, such as gallium oxide (Ga_2O_3) and aluminum nitride (AlN). We are researching and developing novel vertical device architectures for 1200 V GaN transistors, AlN-based lateral transistors that bring the advantages of current GaN transistors to the 1200 V node, and new Ga_2O_3-based transistors in lateral and vertical device architectures. Both aim for 1200 V applications or even higher blocking voltages.

We have successfully demonstrated vertical GaN transistors based on GaN substrates, as well as on foreign substrates like sapphire. Our vertical GaN diodes have already demonstrated 1600 V breakdown voltage. Using substrates with large wafer diameters is also important to be able to compete with SiC-based devices in terms of cost. We have already successfully transferred the GaN layers of the vertical diode wafer from sapphire to a metal wafer. This has enabled us to realize true vertical devices based on a cost-effective substrate technology.

New AlN-based lateral FBH transistors use the device concept of lateral GaN transistors, while featuring a higher power density up to 2000 V blocking voltage. 950 V / 10 A switching transients demonstrate their application potential in kW-range power converters. Our lateral Ga_2O_3-based transistors with up to 1800 V breakdown voltage have been used for 400 V switching events. This is so far the highest reported switching voltage for Ga_2O_3-based transistors worldwide. First vertical FBH Ga_2O_3 transistors showed an average drift zone field of 270 V/µm. This is higher than the theoretical limit for GaN or SiC, demonstrating that the high breakdown field promised for the Ga_2O_3 material can be translated into real devices.

>> *Power converters and switching transistors play a crucial role in enabling efficient energy conversion across industries.*



Interested?

Then please get in touch with us!

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Oliver Hilt (m.) with core team members: Kornelius Tetzner (l.) and Eldad Bahat Treidel (r.).

Benefits of a cooperation with FBH

+ **Internationally recognized** for power and RF devices based on versatile wide- and ultrawide-bandgap semiconductors: (Al)GaN, AlN, Ga_2O_3

+ **Highly-skilled** scientific team in epitaxy, device processing, and characterization

+ **Bridging the gap** between basic and application-oriented R&D due to close cooperation with universities and industry

+ **Benchmarking capabilities** for (Al)GaN, AlN, Ga_2O_3 technology approaches

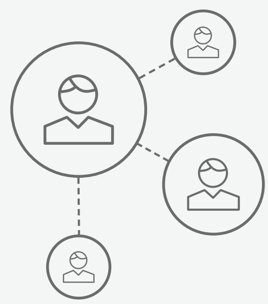
+ **Developing supply chains** with German and European technology partners – from semiconductor crystals to power converters

+ **Full process chain** available in-house – from epitaxy to devices and modules

  – Internal feed-back loop enables fast response time for technology improvements, e.g. electrical measurements → epitaxial design

  – High-resolution processing, from 1 cm x 1 cm samples up to 4" wafers

Ways of cooperating with us



⇢ **Joint research project**

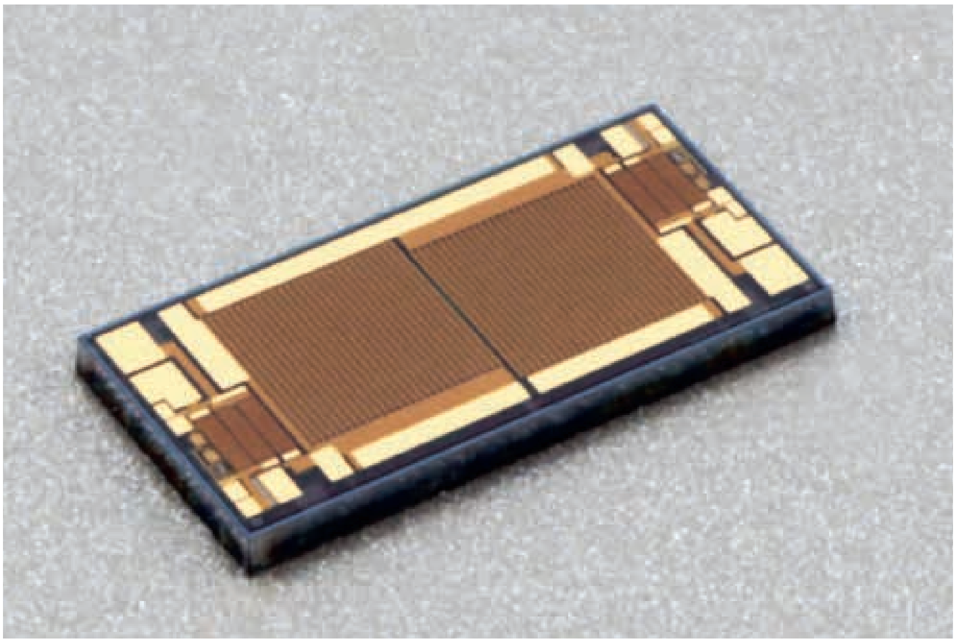
⇢ **Industrial contract**

⇢ **Direct sales**

Competencies and capabilities in power and RF technology research – from design and epitaxy to integrated circuits and power modules

- Monolithic integration of gate drivers and power transistors based on AlN-on-SiC: modeling, simulation, design, processing, assembly, and characterization
- Devices from AlN-on-AlN platforms for ultra-high breakdown voltage applications: design, processing, and characterization
- Gallium oxide-based power transistors in lateral and vertical architectures
- State-of-the art cleanroom facilities (up to ISO 4) for epitaxy, processing, device and module development
- Comprehensive reliability and robustness testing of RF and power devices

Pushing performance limits: aluminum nitride-based power devices



Monolithically integrated high-voltage half-bridge chip with integrated gate drivers based on the AlN-on-SiC platform.

Aluminum nitride (AlN) is a particularly promising material that enables us to maximize the performance potential of lateral power electronic devices beyond the state given by today's GaN transistors. Lateral GaN transistors have not yet approached their theoretical power density material limit. One major reason for this is the usually required GaN buffer compensation doping. Using the ultrawide-bandgap material AlN (6.2 eV band gap) as buffer layer instead would allow for excellent GaN transistor channel confinement. Compensation-doping is then no longer necessary, and related dispersion effects should be eliminated.

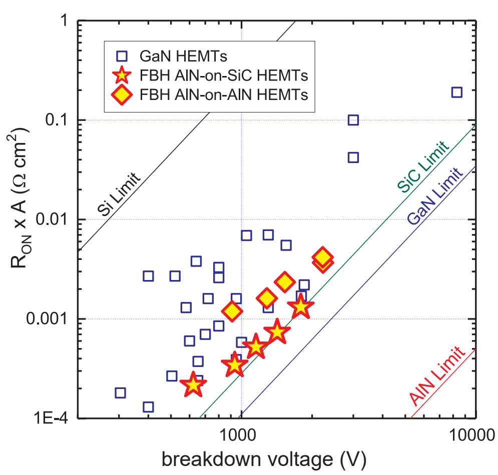
AlN-based power-electronic devices may generally benefit from the exceptionally high critical electric field strength of the material, estimated as > 10 MV/cm and thus approximately three times higher than for GaN. The high AlN thermal conductivity of ~ 340 W/(m·K) additionally enables good heat dissipation from the active power device structure. At FBH, we grow AlN usually on foreign substrates sized up to 4 inches, which offer a cost-efficient solution. In parallel, we are also developing homoepitaxial growth on AlN substrates sized up to 30 mm, which improves the layer quality.

Enabling high-performance half bridges and bi-directional transistors: AlN-on-SiC platform

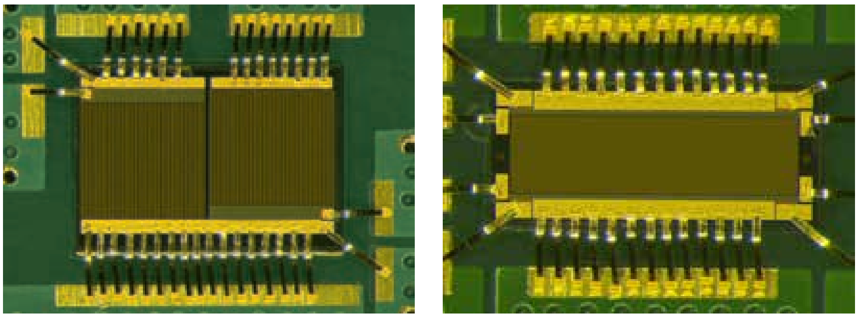
Lateral AlN-based HEMTs using an AlN buffer layer grown on silicon carbide (SiC) substrates enable to circumvent performance issues occurring in GaN-based HEMTs. This results, for example, in low dispersion and better channel confinement.

We have grown AlGaN/GaN/AlN HEMTs on 4-inch SiC substrates and demonstrated a drift zone breakdown voltage scaling of 140 V/µm. This is approximately 20 % higher than for conventional GaN HEMT devices. Devices with 1790 V breakdown voltage have been realized. The power figure of merit was calculated as $V_{Br}/(R_{on}*A)$ = 2.4 GW/cm², which is superior to most lateral GaN-based devices.

The lateral transistor device architecture allows for monolithic integration of power switches, gate driver, along with simple sensing and logics elements. But it is only due to the excellent electrical insulation of both AlN buffer and SiC substrates that enables us to integrate the high-voltage power switches on chip to monolithic half-bridges and bi-directional transistors without being hampered by back-gating losses. Such AlN-based power ICs reduce parasitic wiring inductances in the switching cell power loop and



Power density benchmarking plot for lateral switching transistors based on GaN and AlN.

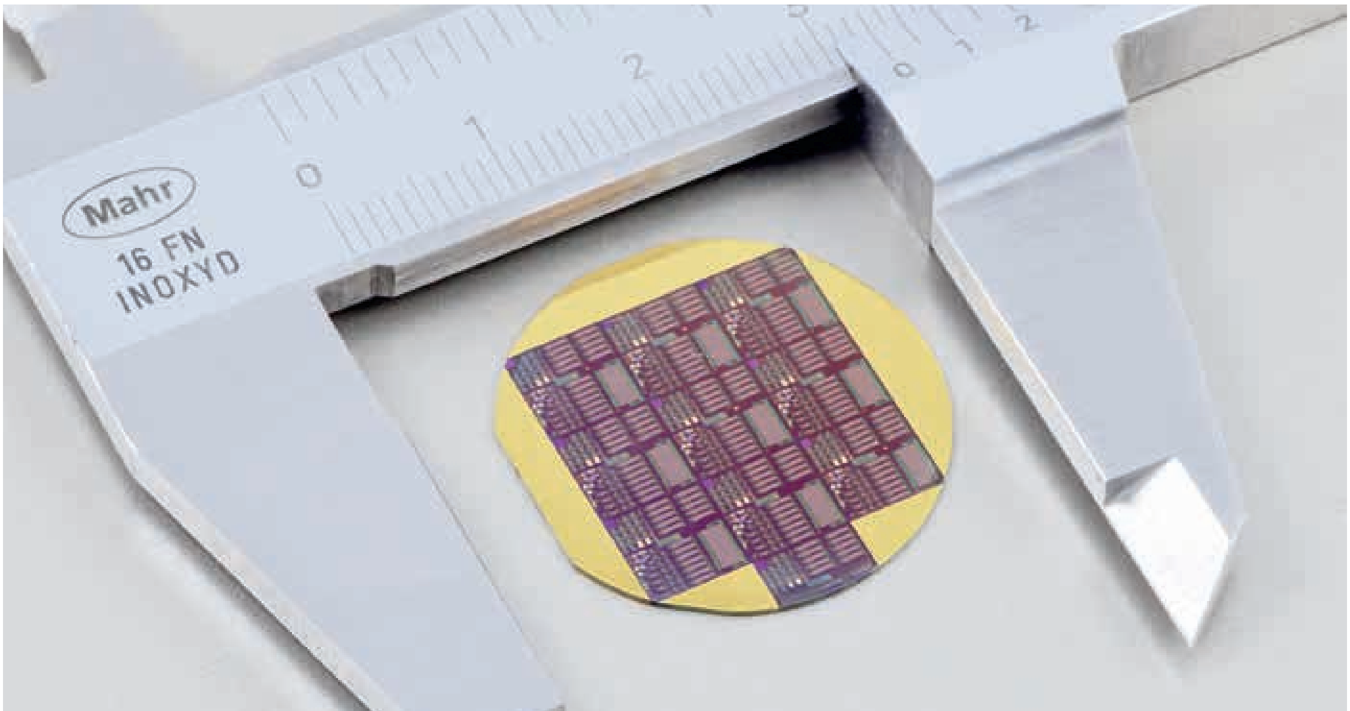


Monolithically integrated 130 mΩ/650 V half-bridge chip (left) and bi-directional transistor chip (right) on PCB submounts.

gate-driving loops. And they are the key to benefit from the particularly high device switching speed on system level. Power converters can operate at higher switching speed, converter volume and mass can be reduced. With our AlN-on-SiC platform we realize power transistors and monolithically integrated half bridges for 400 V/2 kW DC-DC converters in collaboration with Technische Universität Berlin as well as 48V-to-1V point-of-load converters.

Record values due to reduced defect density: AlN-on-AlN platform

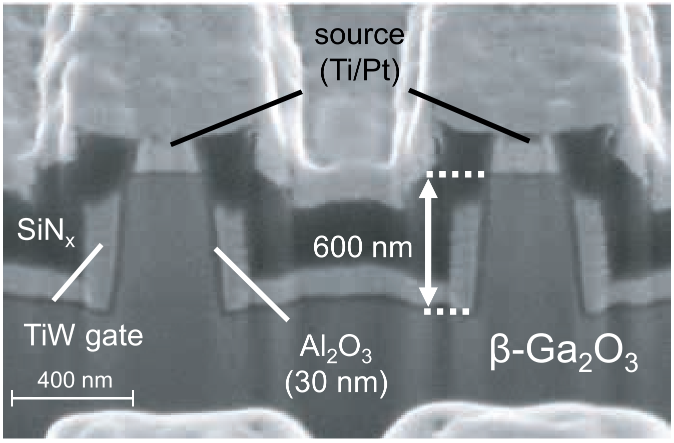
Although small in size, mono-crystalline AlN substrates with dislocation densities < 1e4 cm^{-2} can be used to grow AlGaN/GaN/AlN semiconductor stacks. Such homoepitaxy significantly reduces defect density in the active semiconductor layers, enhancing reliability. It also eliminates the thermal boundary resistance between substrate and buffer layer, lowering thermal impedance. We have demonstrated AlGaN/GaN/AlN HEMTs on AlN substrates, which show an average breakdown voltage scaling of 125 V/µm and a power FOM 1.17 GW/cm^2. These are record values for high-voltage GaN channel transistors on AlN substrates. More than 2200 V breakdown voltage was achieved. These results emphasize the applicability of AlN for very high voltage modules with good isolation quality in lateral device technology. Our current research focuses on using an enlarged AlN wafer size of up to 30 mm and developing monolithically integrated power ICs on the AlN-on-AlN platform.



1-inch AlN-on-AlN wafer with processed power transistors.

Material for future high-voltage transistor generations: gallium oxide

The demands on power electronic devices continue to rise, calling for power converters with improved efficiencies at much higher voltage levels. Thus, the hunt for high-performance materials of the future with wider bandgaps continues. This brings materials such as gallium oxide (β-Ga_2O_3) into focus. The ultrawide-bandgap semiconductor possesses a bandgap of 4.8 eV. With an estimated dielectric strength of 8 MV/cm, it has the potential to drastically reduce the gate-to-drain distance, thus allowing to fabricate more compact and efficient transistor devices with reduced switching and conduction losses. Therefore we have launched research activities at FBH in recent years and joined forces with the Leibniz Institute for Crystal Growth to develop and process lateral and vertical power switching transistors based on β-Ga_2O_3.



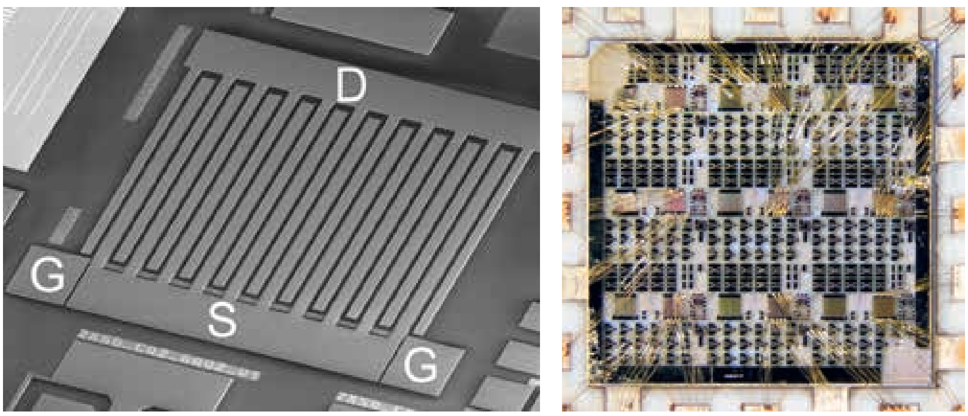
SEM cross-section image of the fully processed β-Ga_2O_3 FinFET device with a 1.2 µm pitch of the fins.

Lateral design – for fast and highly efficient next-generation switching devices

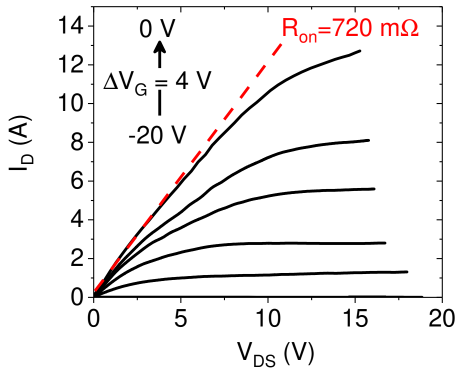
We have successfully fabricated lateral Ga_2O_3-based transistor devices, featuring a gate width of 10 mm that show record absolute currents of up to 2.5 A. In collaboration with Technische Universität Berlin, we have also demonstrated fast and reproducible switching with such devices at blocking voltages up to 400 V and switching speeds of 78 V/ns. These results along with the achieved high breakdown strength of 2 MV/cm emphasize the high potential of this material to realize fast and highly efficient power switching devices of the next generation. Recent device processing on 2-inch Ga_2O_3 wafers allowed for even larger device dimensions, yielding 750 mΩ switching transistors with more than 10 A current capability. Such devices pave the way towards first demonstrators of real-life scenario Ga_2O_3-based power converter systems.

Vertical design – optimal for high-voltage, high-current applications

To use the full potential of β-Ga_2O_3 material properties when targeting high-voltage/high-current applications, a vertical device structure is advantageous for active devices. This has already been widely demonstrated for vertical Schottky barrier diodes based on β-Ga_2O_3. Main advantages include the lower chip area at high voltage levels, ideal separation of high-voltage potentials, improved reliability, and thermal performance as well as the potential to reach higher current levels. We have opted for the FinFET topology. This enables strong electrostatic gate control by double gating the channel at each fin structure. These characteristics allow for enhancement-mode operation, making this structure very attractive for future high-power electronic applications. Very recently, we have realized the first vertical β-Ga_2O_3 FinFET at FBH, demonstrating enhancement-mode properties and an average breakdown strength up to 2.7 MV/cm. This value is already significantly higher than what has been measured in lateral β-Ga_2O_3 devices processed at FBH so far, despite the lack of edge termination in this initial device version. This emphasizes the high potential of using a vertical device architecture for high-power electronic applications.



Multi-finger β-Ga_2O_3 switching transistor with 10 mm total gate width (left) and β-Ga_2O_3 chip wire-bonded on a PCB submount (right).



Output characteristic of an upscaled β-Ga_2O_3 switching transistor for converter applications.

Vertical gallium nitride devices – a competitive technology for high-power conversion systems

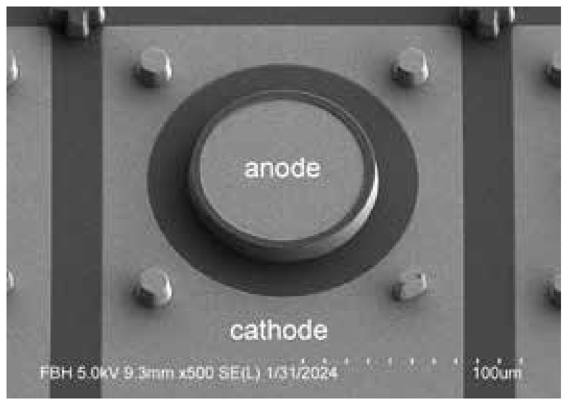
In high-voltage power conversion systems, a vertical semiconductor device topology is favorable: It combines thick epitaxial layers to block high voltages in off-state and a very high current density for low resistance during on-state. Moreover, this topology offers a reduced thermal impedance as compared to a lateral device topology. Due to the superior GaN material properties as compared to SiC and the predicted lower market prices, the development of vertical GaN-based power switching devices has accelerated in recent years. This allows them to compete with SiC-based devices in the 1.2 kV class.

To make these devices ready for the market, we are addressing materials and process technology challenges that need to be overcome. Among these are sufficiently thick MOCVD-grown GaN drift layers with well-controlled low doping concentration and the realization of laterally confined *pn* junctions. These are crucial to ensure high blocking voltage, avalanche capability, and short-circuit robustness. Thus, a significant part of our work is focused on epitaxial growth and characterization of very thick *n*-type GaN drift layers and *p*-type GaN for junction forming on native GaN as well as on foreign sapphire substrates.

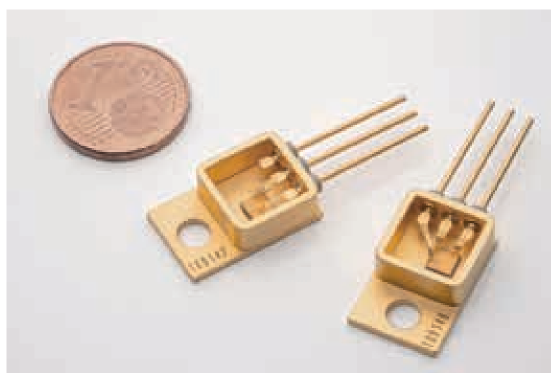
We have already demonstrated GaN-based vertical *pn*-diodes as a monitoring tool to assess thick epitaxial layers grown on various free-standing GaN and foreign substrates. These vertical diode structures are also used as manufacturing process modules and for edge termination topologies. Vertical GaN devices fabricated on native GaN substrates feature a low dislocation density, which is beneficial in supporting the high blocking strength with low off-state leakage currents and avalanching capability.

Vertical GaN power switching transistors require a different topology than Si- or SiC-based devices. This is due to the absence of mature area-selective deep implantation and activation of *p*-type GaN regions. Therefore, a gate module based on epitaxially grown layers is required. We have developed and demonstrated two different types: *n*-channel trench MOSFETs and *n*-type FinFETs. For power switching transistors; trench MOSFETs with epitaxial *n*-*p*-*n*-junction feature secure normally-off characteristics by carrier inversion. They benefit from our robust manufacturing technology that results in large-area devices with good yield. FinFETs only need *n*-type GaN layers and use highly down-scaled fins to achieve normally-off characteristics, combining high channel mobility with low parasitic capacitances and large current density per chip area.

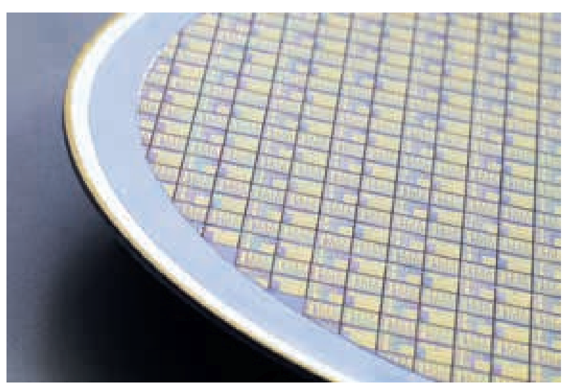
To be commercially competitive with 1.2 kV class SiC-based transistors, we need to overcome limitations in wafer size, price, and substrate conductivity. Thus, omitting the GaN substrate may be essential for commercial success. Membrane GaN layers grown on sapphire substrates that are then lifted off using a laser technique and transferred to a metallic substrate open a path towards true vertical GaN devices at reduced cost. We have successfully demonstrated true vertical GaN membrane diode structures bonded to a tungsten metal wafer. After growing thick epitaxial GaN layers on a sapphire substrate, *pn*-diodes are manufactured using FBH's frontend process line. The sapphire substrate is completely separated from the GaN epitaxial layers to create a 4-inch GaN membrane sheet. The membrane's back side is then bonded to a tungsten metal wafer, forming true 1.2 kV vertical devices.



SEM picture of a processed circular quasi-vertical pn diode.



Packaged GaN trench MOSFETs on GaN substrate.



Vertical GaN Schottky diode structures after substrate transfer from 4" sapphire to tungsten.

The Ferdinand-Braun-Institut (FBH) is an application-oriented research institute in the fields of high-frequency electronics, photonics, and quantum physics. It 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 such as communications, energy, health, and mobility. Specifically, FBH develops light sources from the near-infrared 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 realizes electronic devices based on wide- and ultrawide-bandgap semiconductors for efficient and compact power converter systems.

The FBH is a center of competence for III-V compound semiconductors covering the full range of capabilities, from design through fabrication to device characterization. Within the Research Fab Microelectronics Germany (Forschungsfabrik Mikroelektronik Deutschland – FMD), FBH 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 and strategic partnership 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 thereby offers its international customer base complete solutions and know-how as a one-stop agency – from design to ready-to-use modules and prototypes.

Imprint

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

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Print: Pinguin Druck GmbH

Layout: telegrafik berlin

Images:
Cover: FBH's 1" AlN, 2" Ga_2O_3 &
4" AlN-on-SiC wafers
B. Schurian: wafer images on cover,
p. 7 (middle)
P. Immerz: pp. 3, 4, 5 (bottom),
7 (bottom), 8
further images: FBH

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