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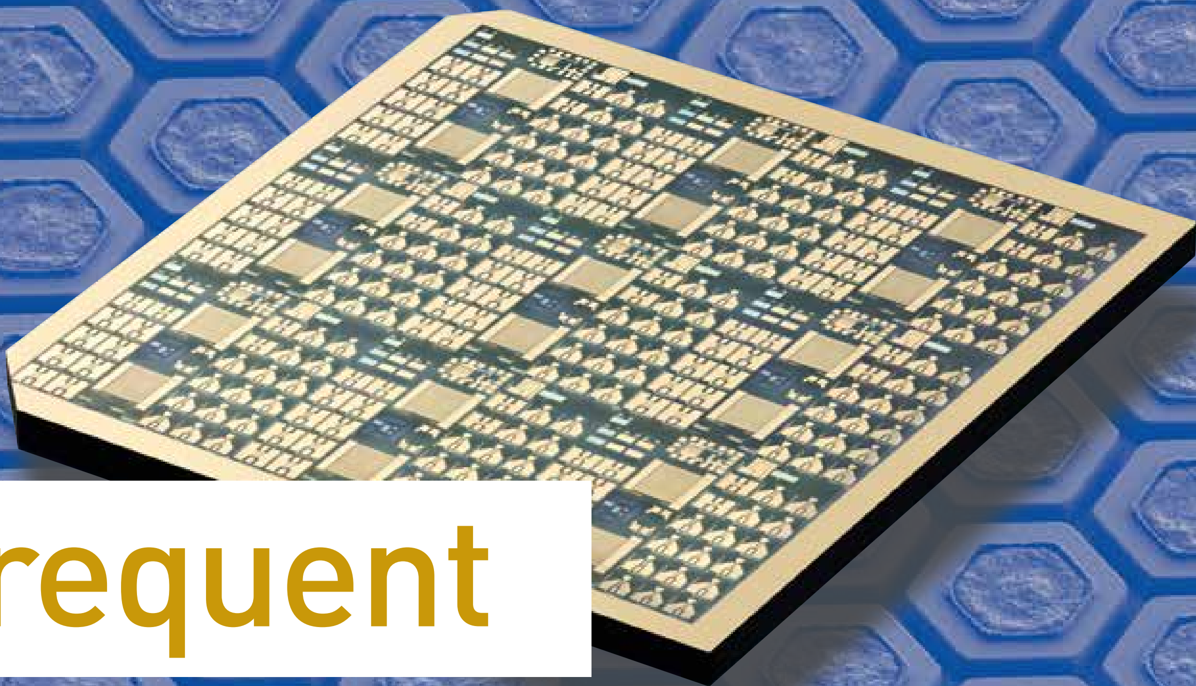

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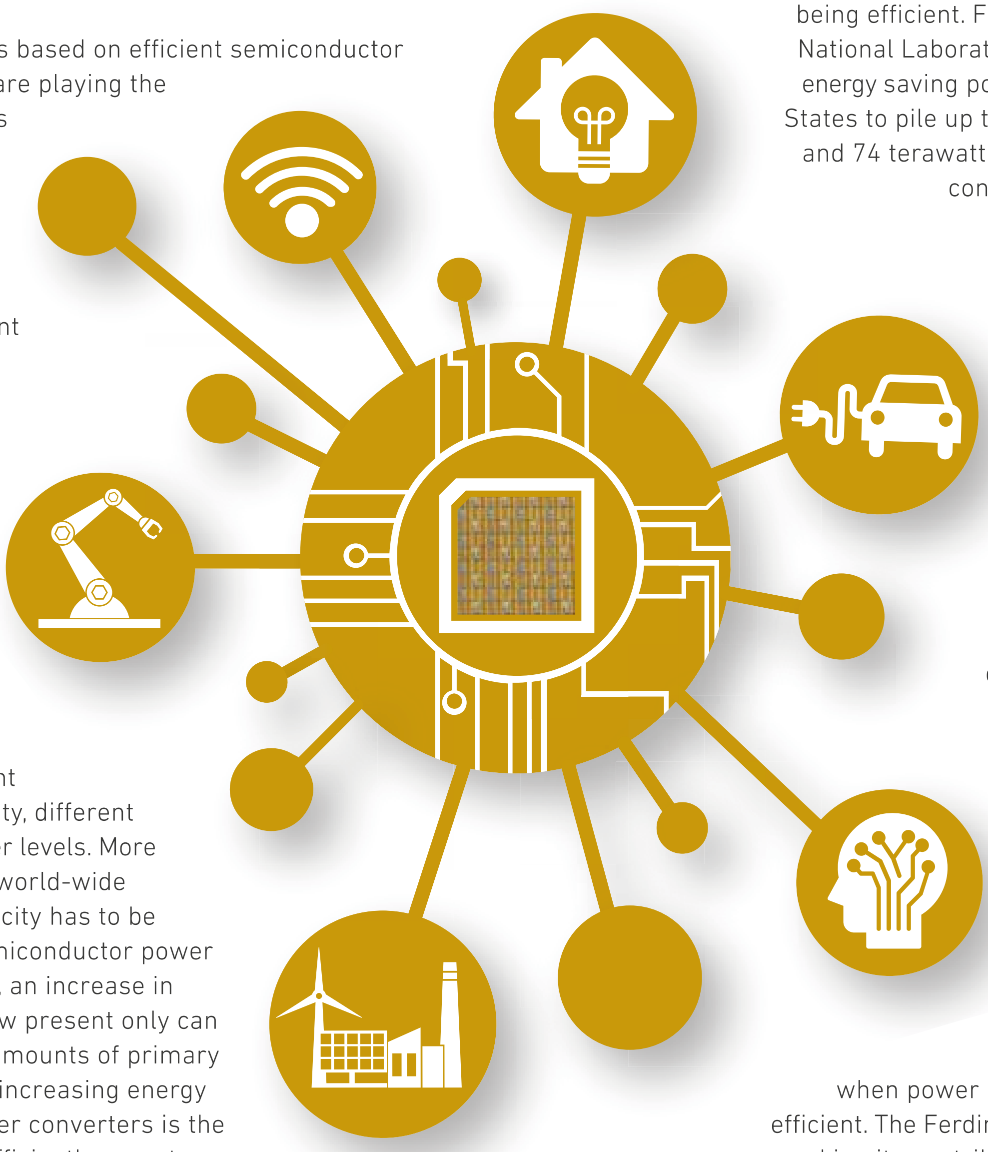
Wide bandgap devices & modules for efficient power electronics

- coping with the demands of energy-hungry societies
- integration concepts for efficient GaN converters
- novel materials & device concepts

Novel power electronics to cope with energy-hungry modern societies

Our modern society is facing an ever increasing penetration of communication and computing devices and systems in everyday life. This process will even intensify and significantly influence areas like mobility and industrial production. The challenge is to combine internet of things with a low carbon dioxide consuming society. Novel approaches for energy-efficient conversion of electrical energy are needed to power modern digital society.

Power converters based on efficient semiconductor power switches are playing the crucial role in this context. These devices often go unnoticed by the general public but are taking over the important task of converting electricity. Electrical energy delivered from the grid or from batteries – like in electric cars – needs to be transformed to various systems, requiring different forms of electricity, different voltage and power levels. More than 50 % of the world-wide generated electricity has to be converted by semiconductor power converters. Thus, an increase in efficiency by a few present only can save enormous amounts of primary energy. Actually, increasing energy efficiency in power converters is the prerequisite to efficiently operate our energy-hungry digital infrastructure and electrically driven transportation systems – and last but not least to cope with their expected growth rate.



Wide bandgap semiconductor devices – transistors and diodes – as explored at FBH are playing a key role in these kinds of developments. They have the potential to reduce the power converter volume by 50 % and raise efficiency levels up to 99 %. This corresponds to reducing the size of a laptop power supply to the scale of a mobile phone charger.

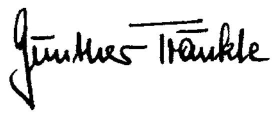
Semiconductors like gallium nitride (GaN), aluminum nitride (AlN) or gallium oxide (Ga_2O_3) all feature a very high breakdown strength. Hence they enable power switching devices with unprecedented power density and low switching losses – the most important conditions for being efficient. For 2025, the Oakridge National Laboratory has estimated the energy saving potential for the United States to pile up to a value between 35 and 74 terawatt hours per year when consequently using wide bandgap semiconductors. As a result, the electrical power delivered by six to eight average coal-fired power plants could be saved – avoiding the emission of billions of tons of carbon dioxide. Extrapolating these values to the whole world would add up to a truly impressive figure.

It is evident that demands requested by modern societies can only be realized when power electronics gets more efficient. The Ferdinand-Braun-Institut is making its contribution with innovative developments, ranging from lateral and vertical GaN power transistors to ß-Ga_2O_3 power switching devices and AlN-based electronics in various implementations. FBH is closely cooperating with industry and academic partners, thus working on power electronic systems, circuit design and power electronic measurement techniques in short development cycles.

Editorial

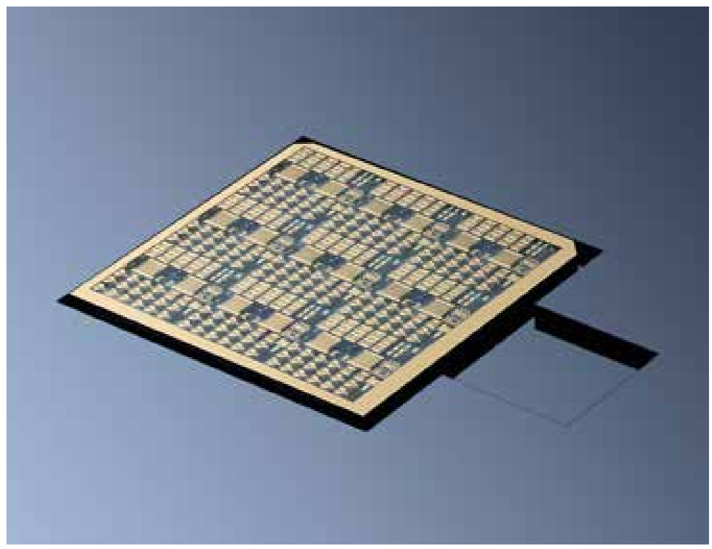
The responsible use of resources is one of today`s key challenges, especially since energy consumption will continue to rise with the demands. Thus, we are all called upon to make our commitment – from consumers to reduce their energy consumption to technical solutions that consume less energy. The Ferdinand-Braun-Institut contributes with its developments targeting energy-efficient conversion of electrical energy.

We have compiled an overview of different FBH approaches involving novel high-performance materials as well as efficient semiconductor power switches used in power-electronic converters. In addition, our short news keep you posted on further developments.

I wish you an inspiring reading, 

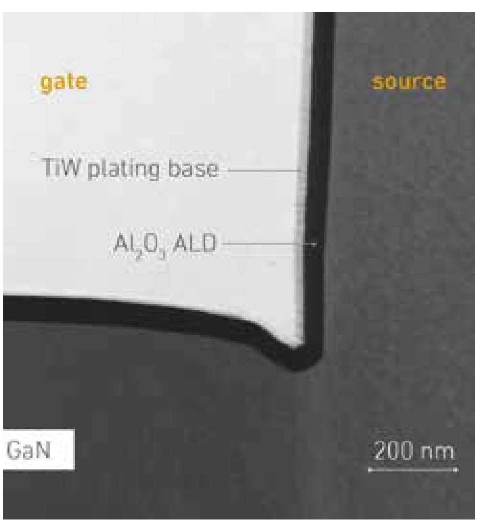
How to process small substrates

Novel semiconductor materials such as freestanding gallium nitride wafers and gallium oxide substrates are not always available in diameters larger than 1 inch. For a competitive device development, however, it is necessary to realize extremely precise submicron lithographic dimensions with alignment accuracies between different lithography levels of better than 200 nm. Therefore, FBH has developed a special chuck technology based on laser structuring of silicon (Si) wafers and Si-on-Si wafer bonding. This method allows precise processing of 1 x 1 cm^2 and 1-inch substrates in an i-line wafer stepper environment. The small samples are aligned to a definite mechanical stopper integrated into the chuck. The chuck itself mimics a 3-inch wafer, thus enabling wafer stepper pre-alignment and exposure alignment. This allows realizing sub-micron structures with the required precision. Thus, devices fabricated with this technique can be easily compared to other types of devices having similar dimensions.



Substrate holder for wafer stepper lithography

Advanced ALD processes for improved transistor functionality



The electrical properties of gate insulators have a crucial influence on the GaN MISFET's gate modulation properties and are a key for proper transistor functionality. Therefore, the FBH has been systematically investigating and optimizing the gate insulator deposition process. To this end, different Al_2O_3 films were atomic layer deposited (ALD) by two methods, thermal ALD (ThALD) and remote plasma-enhanced ALD (PEALD). Subsequently, the films were electrically analyzed by capacitance-voltage and electrical breakdown strength measurements. The deposition was performed in an ALD system (SENTECH SI PEALD) and combined with an in situ ammonia plasma surface pretreatment. While the PEALD films show high breakdown robustness, the ThALD films offer a lower capacitance-voltage hysteresis. Additionally, an alternating layer utilizing both methods was deposited for the first time, combining the advantages of each approach. It exhibits superior electrical properties with less hysteresis, indicating reduced oxide film charging, lower flat-band forward voltage shift and high electrical breakdown robustness.

Hybrid and monolithic integration needed for efficient GaN converters with high power density

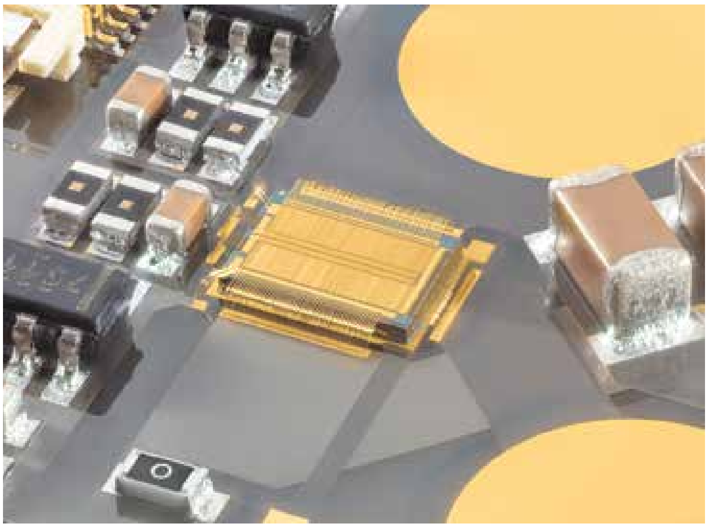


Fig. 1: Monolithically integrated 600 V, 170 mΩ GaN half bridge chip mounted on AlN-based hybrid platform

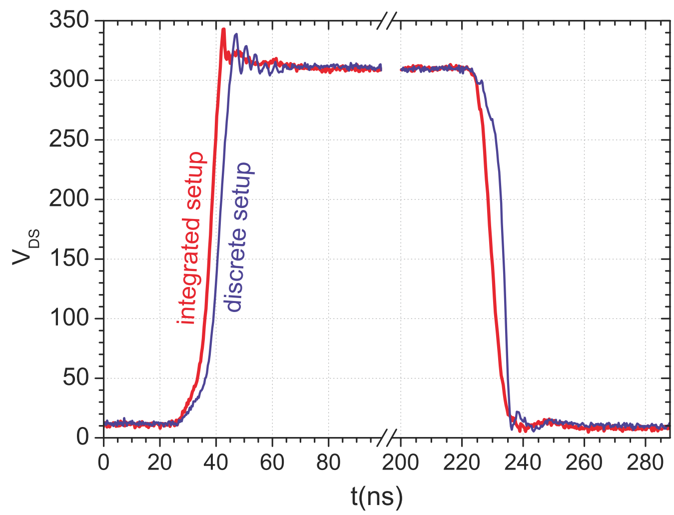


Fig. 2: 6 A, 300 V turn-off and turn-on voltage transients with the integrated half-bridge configuration of Fig. 1 (red) compared to a conventional PCB-based packaging concept (blue)

Increasing the power density of switch-mode power-electronic converters requires higher operation frequencies and thus transistors with high switching speed. GaN-based 600 V switching transistors feature a particularly low gate charge and a low output capacitance which may result in switching transients of up to 200 V/ns slew rate. This is why GaN transistors demonstrate clear advantages in terms of switching speed over Si-based superjunction metal-oxide-semiconductor field-effect transistors (MOSFET) and even over SiC MOSFETs. Essential for gaining benefit from high-speed switching in a power converter system is the realization of a low-inductance environment for both the gate and the power loop. However, typical parasitic inductances from packaging and package inter-connects in the nH-range already generate ringing of switching transients in the 10 ns timescale. Increased switching losses and device over-voltage stress are the consequence, resulting in reduced converter efficiency.

Low-inductance designs with particularly small current loops are required for the circuit board layout and for transistor packaging to take full benefit of the GaN transistor's inherently high switching speed. To optimize GaN-based converter switching cells, FBH uses its own established 600 V normally-off GaN technology that is based on a p-GaN gate module. As a hybrid integration approach FBH developed an AlN-based 600 V, 10 A two-layer platform. It enables a very compact assembly of the gate loop and the power commutation loop for a GaN-based half bridge (shown on cover, bottom). Two stacked metal layers allow for particularly small vertical power loops. The platform supports die bonding and wire bonding as well as SMD soldering of gate driver integrated circuits (ICs) and capacitors. The AlN substrate serves as electrically insulating heat sink with low thermal impedance. For further power commutation loop reduction FBH combined two 600 V, 170 mΩ GaN transistors on one chip as monolithically integrated half bridge (Fig. 1). Indeed, the 6 A, 300 V switching transients (Fig. 2) of the integrated half bridge show faster turn-on, faster turn-off and less ringing as compared to a setup with traditional PCB-mounted discrete transistors from the same GaN wafer.

Unlike for Si-based vertical MOSFETs of the 650 V class or SiC FETs, the GaN heterojunction field-effect transistor (HFET) lateral design makes source, gate and drain accessible from the chip top-side. Moreover, it offers the opportunity to laterally integrate different device functionalities on one die and to realize very fast GaN-based ICs. A 60 V, 1 A half bridge chip with integrated power switching transistors and integrated gate drivers (Fig. 3) was designed to explore power conversion at switching frequencies as high as 100 MHz. A power loop efficiency of 87 % was achieved for 14 W power conversion from 30 V to 20 V.

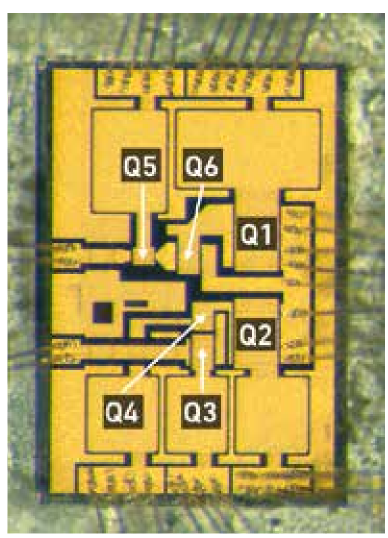


Fig. 3: GaN HFET half-bridge chip with integrated gate drivers for 100 MHz power conversion. The individual half-bridge switches Q1 and Q2 and the gate driver transistors Q3-Q6 are indicated

Novel materials and device concepts targeting future high-power switches

New wide bandgap materials combined with innovative device concepts have the potential to further increase power density and to overcome challenges of lateral gallium nitride (GaN) technologies. In this connection, FBH has started new initiatives targeting novel power switching devices. True vertical GaN power transistors fabricated on free-standing GaN substrates and devices relying on thermally highly conductive but electrically insulating aluminum nitride (AlN) as buffer material are among FBH's R&D foci. Another emphasis is on the new material gallium oxide.

Vertical GaN high current power switching transistor for direct laser pulsing

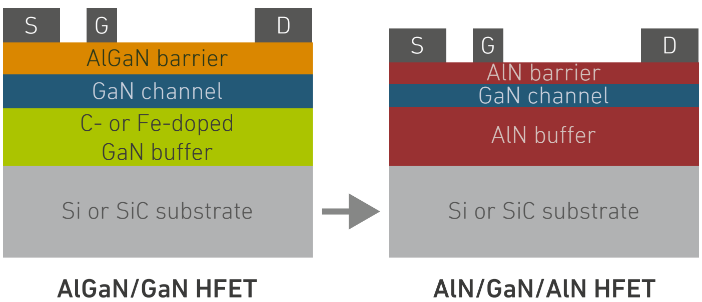
GaN vertical MISFETs

Vertical GaN-based field effect transistors for high voltage power switching applications have the potential to outperform Si- and SiC-based competitors in terms of power density and switching speed. FBH's vertical GaN MISFET technology currently focusses on fast pulsed laser driving applications with maximum voltages < 100 V. Drivers for pulsed lasers are required to deliver very high currents up to 250 A with pulse lengths as short as 3 – 10 ns. Vertical GaN MISFETs are particularly suited for realizing very steep current slopes due to their low output capacitance and gate charge figure-of-merits. Further, the vertical GaN transistor topology enables a compact assembly to achieve ultimately small current loop inductances for fast laser pulsing. The enhancement-mode trench MISFET concept is chosen since it allows a normally-off gate drive characteristic, enables aggressive device downscaling and high current densities per unit area. The vertical GaN transistors have been successfully integrated with a GaAs-based diode laser using chip-on-chip mounting schemes. This arrangement demonstrated 4 W laser pulses at 905 nm wavelength with 3.5 ns pulse duration.

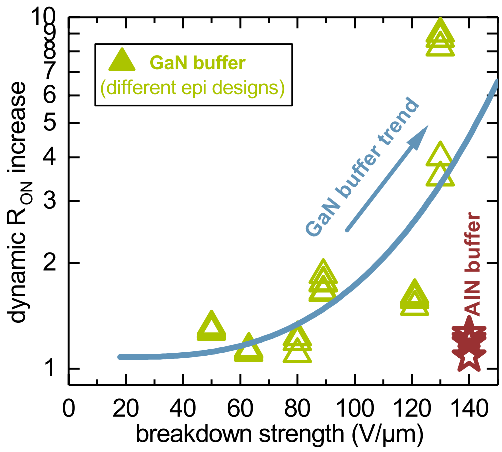
From GaN transistors to AlN-based electronics

Lateral GaN-based transistors (HFETs) from the FBH have recently demonstrated superior performance as high-speed switches in small and light-weighted power converters up to 600 V. This current technology requires compensation doping with iron or carbon to keep the channel electrons well confined at high drain voltages and to suppress off-state leakage currents. Dopant-related trap states are, however, the root cause for dispersion effects, frequently seen in GaN transistors.

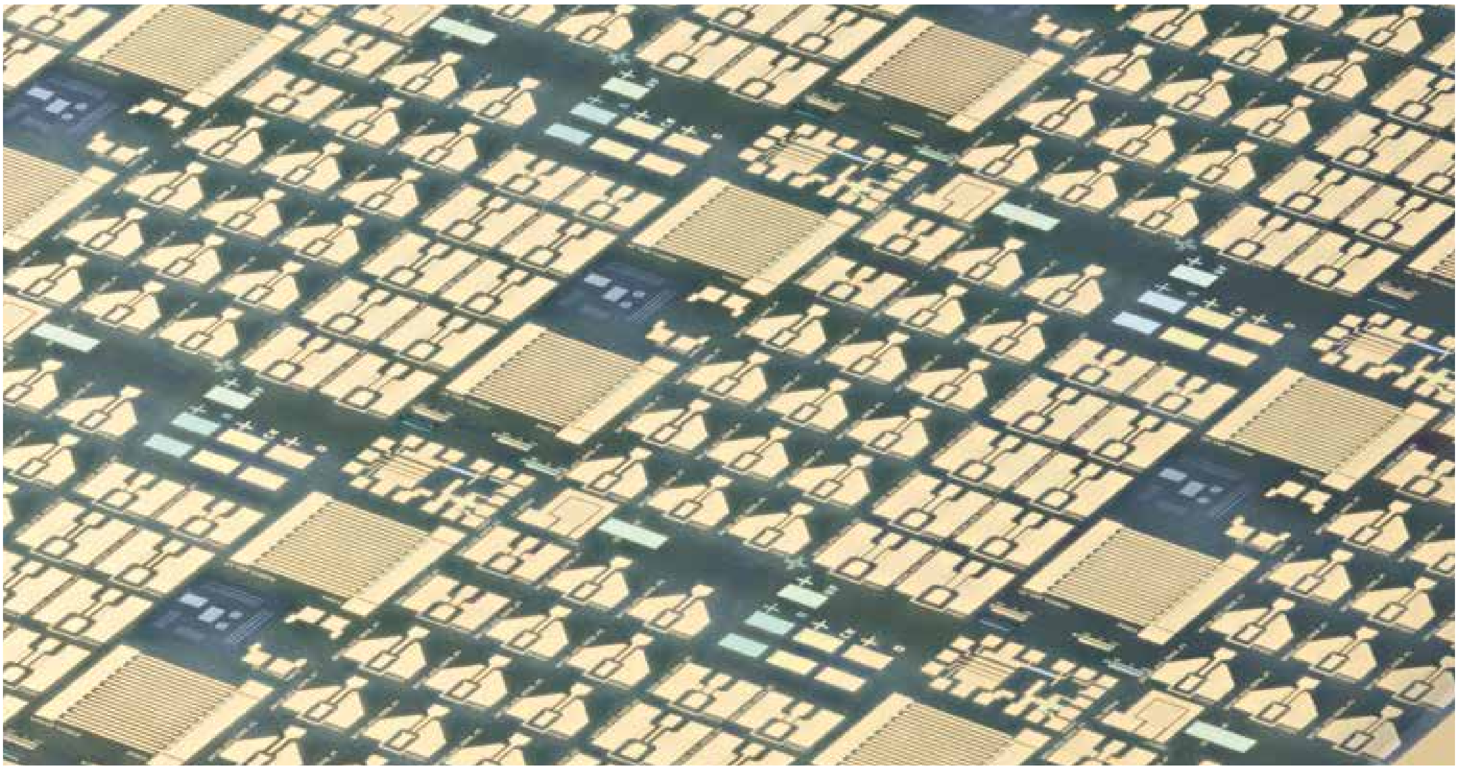
The FBH now targets new aluminum nitride (AlN) based devices that promise to surmount performance limitations inherent to GaN HFETs. Using the ultra-wide bandgap



Conventional AlGaN/GaN HFET structure with either carbon- or iron-doped GaN buffer (left) and new AlN-based HFET structure with non-doped AlN buffer and with AlN barrier (right)



Dynamic on-state resistance increase vs. breakdown voltage scaling for different GaN transistors using either compensation-doped GaN buffer structures (green) or an AlN buffer (red)



Gallium oxide chip with lateral transistor and measurement structures

material AlN as buffer material does not require compensation doping and allows for excellent transistor channel confinement. Dispersion effects thus should reduce. FBH now confirmed the principal benefits of AlN buffer layers and demonstrated AlGaN/GaN HFETs with higher breakdown strength and with less dispersion as compared to AlGaN/GaN HFETs with conventional GaN buffer. The new AlN-buffer devices combine a superior breakdown voltage scaling of 140 V/mm gate-drain separation with low increase in dynamic on-state resistance of only 18 %, when pulsing for 0.2 µs from 65 V off-state drain bias into device on-state. In comparison, different GaN-buffer epi designs feature either a low dynamic R_{ON} – with poor breakdown strength – or a high breakdown strength – but with a high dynamic R_{ON}.

High-performance material for energy-efficient power electronics

The ultra-wide bandgap semiconductor gallium oxide ($ß\text{-}Ga_2O_3$) has received great attention in recent years due to its unique material properties. It is considered as an attractive alternative to conventionally used materials such as SiC or GaN for future power electronic applications. The estimated dielectric strength of 8 MV/cm offers the possibility to drastically reduce the gate-to-drain distance, thus allowing to fabricate more compact and efficient transistor devices with reduced switching and conduction losses. This is emphasized by Baliga's Figure of Merit (BFOM), describing the basic suitability of a semiconductor material for power switching applications – the BFOM of $ß\text{-}Ga_2O_3$ is a factor of 3,000 higher than that of silicon.

In collaboration with the Leibniz Institute for Crystal Growth, FBH has been developing lateral $ß\text{-}Ga_2O_3$-based power transistor devices on 10 mm x 10 mm substrates. The partners combine improved layer growth of n-type epitaxial layers, exhibiting low defect densities as well as enhanced electron mobility, with an optimized high-resolution process technology using projection lithography. As a result, first transistors were fabricated featuring high average breakdown field strengths of around 2 MV/cm at off-state along with low on-state resistance. These values already outperform the results of more established wide-bandgap device technologies like SiC and GaN and demonstrate the high potential of this promising new material.
[K. Tetzner et al., "Lateral 1.8 kV $ß\text{-}Ga_2O_3$ MOSFET with 155 MW/cm^2 Power Figure of Merit", Electron Device Lett. (2019). doi: 10.1109/LED.2019.2930189]

Research in focus

Next generation LiDAR laser source for line scanners

FBH's high pulse power laser source with a 48-emitter diode laser bar is ideally suited for 3D object detection, e.g., for line scanners in automotive LiDAR. Scanning LiDARs emit rapid laser pulses which are reflected by objects. The return time of each pulse is measured by a detector, thereby creating a point cloud of the measured surface. Unlike point scanners, which capture objects point by point via 2D steering mirrors, line scanners use a laser array. Its light is focused to a line which scans a large area using 1D beam steering. The reflected light is collected via a detector row. The wavelength-stabilized FBH laser source delivers 4–10 ns long optical pulses with >600 W pulse peak power at 905 nm wavelength. The wavelength shifts with temperature by 0.06 nm/K only. The DBR-stabilized laser emission has a width of 0.5 nm and >30 dB side mode suppression. The bar is electrically driven by a new in-house developed high-speed GaN driver providing current pulses of up to 800 A with 100 kHz repetition frequency and higher. The optics were designed and realized by FISBA.

Product in focus

Highly sensitive THz detectors for room temperature operation

The FBH has developed highly sensitive, fast-response and broadband terahertz (THz) power detectors for CW and pulsed operation, which are based on the in-house GaN HEMT MMIC process. This gives the unique opportunity to tailor both transistors and antenna structures for use up to several THz (patent-protected design). The inherent high breakdown voltage and high current capabilities of the FBH process yields robust detectors, which can be used for industrial quality control as well as for biomedical, spectroscopy and security applications. At room temperature a sensitivity of $NEP < 50\,pW/Hz^{1/2}$ is achieved for circular polarized radiation from 90 GHz up to 1.2 THz. The preamplifier provides an RMS = 8 mV noise floor with 100 kHz bandwidth. Moreover, it offers the possibility to chop a THz CW signal. Thus, it allows using a lock-in amplifier to measure even weak CW THz signals. The system can also be equipped with linearly polarized antenna structures.

Save the dates

ICULTA 2020

April 26–29, 2020 – for the second time, ICULTA 2020 brings 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. The conference is organized jointly by 'Advanced UV for Life' – the consortium's office is located at FBH – and the 'International Ultraviolet Association'.
www.iculta.com

27th INTERNATIONAL SEMICONDUCTOR LASER CONFERENCE ISLC2020

October 11–14, 2020 – later in 2020, the FBH together with IEEE is organizing the 27th IEEE International Semiconductor Laser Conference ISLC2020 in Potsdam. The prestigious conference is held every two years and dedicated to latest developments in semiconductor lasers, amplifiers and LEDs.
www.ieee-islc.org

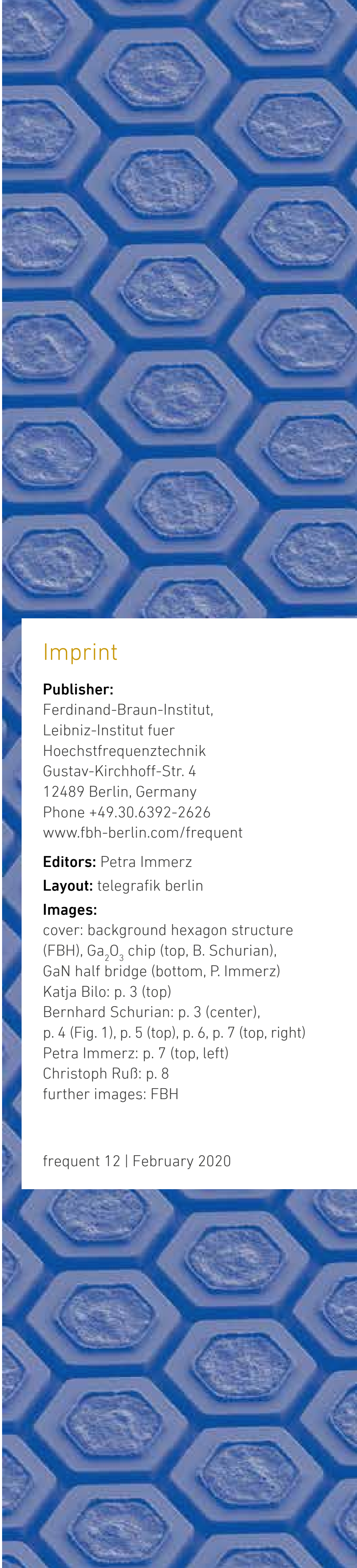
The Ferdinand-Braun-Institut, Leibniz-Institut fuer Hoechstfrequenz-technik (FBH) researches electronic and optical components, modules and systems based on compound semiconductors.

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.



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cover: background hexagon structure (FBH), Ga_2O_3 chip (top, B. Schurian), GaN half bridge (bottom, P. Immerz)
Katja Bilo: p. 3 (top)
Bernhard Schurian: p. 3 (center), p. 4 (Fig. 1), p. 5 (top), p. 6, p. 7 (top, right)
Petra Immerz: p. 7 (top, left)
Christoph Ruß: p. 8
further images: FBH

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