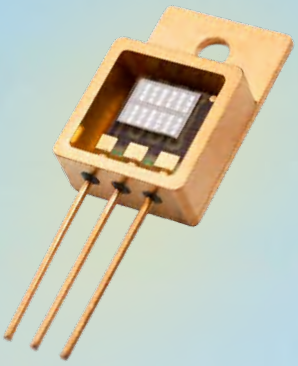

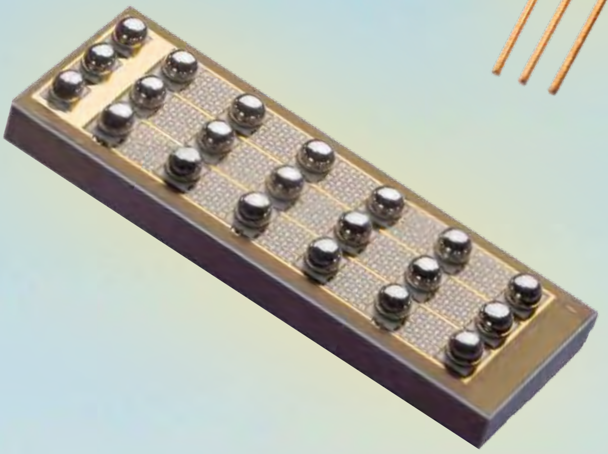

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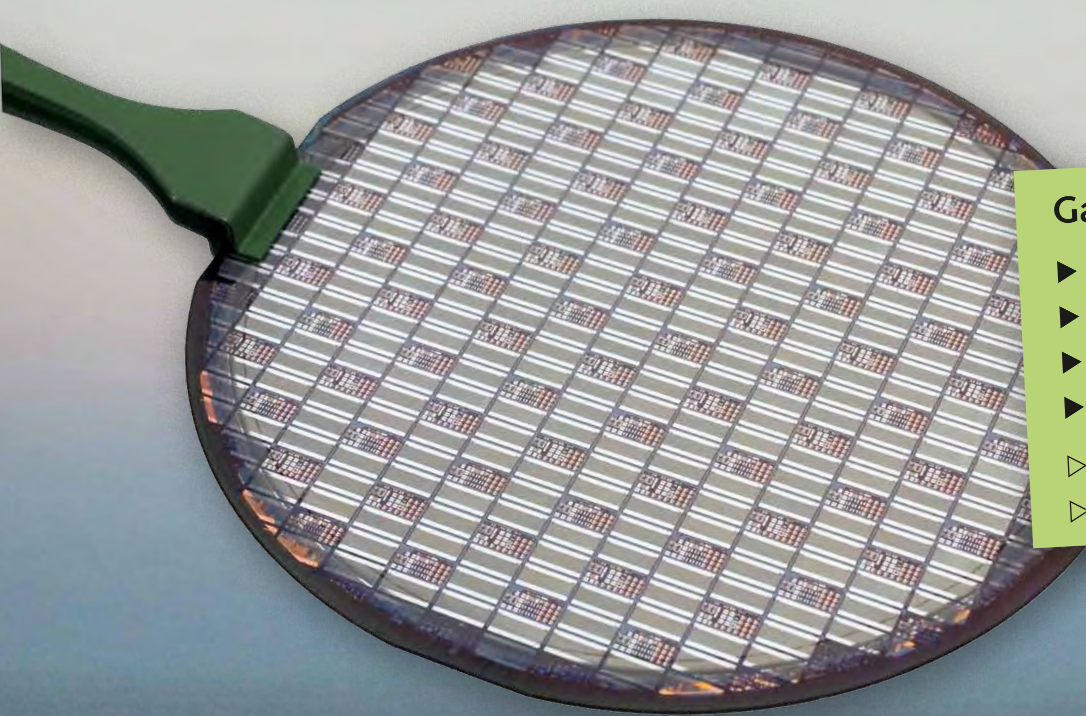
Research news from the Ferdinand-Braun-Institut



GaN power electronics

- ▶ energy-efficient technological solutions
- ▶ high-voltage transistors
- ▶ normally-off transistors
- ▶ Schottky diodes

- ▷ products in focus
- ▷ research in focus

GaN power electronics

for energy-efficient technological solutions

Energy efficiency is one of the most important issues of the future world-wide. Consequently, there is a strong demand for technical solutions consuming less energy or utilizing it more efficiently. A broad range of approaches therefore deals with this topic in multiple technical disciplines. Electric power converters, for example, are integrated in practically every electric and electronic system. They can reduce primary energy consumption by converting either DC or AC current particularly efficient into system-relevant electricity levels. Switching elements with increased power density may further reduce system size and weight and thus save energy additionally. Highly efficient power converters are also indispensable for energy conversion in solar systems, wind power stations and modern electric vehicles as well as for power supplies in mobile base stations and computer systems. Due to the proven high radiation hardness of gallium nitride (GaN) devices, they are becoming increasingly attractive for space applications, in particular, for satellite-based solar energy converters.

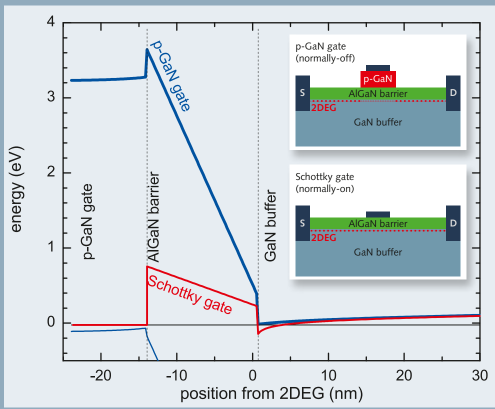
Hence, GaN-based semiconductors are particularly important for the technical realization of such systems. Power converters utilizing the specific GaN material properties are able to switch high power levels at high switching speeds, typically in the MHz range. The resultant adjustments in system design lead to small and light-weighted systems. At a given operation voltage, the on-state resistance of GaN devices outperforms competing silicon (Si) devices by more than one order of magnitude. This potential has been repeatedly verified on laboratory scale at FBH and world-wide—the technology is on the verge of industrial maturity. GaN transistors from the FBH have already passed the high quality requirements for space applications and will soon be implemented on board of the geostationary Alphasat communication satellite.

Key devices for these and further applications in power electronics are normally-off power transistors. They are switched on at positive gate bias and automatically switched off when the gate bias declines back to zero voltage. Therefore, the devices are inherently secure and suitable for energy converters requiring specifically high system reliability. Due to the long-term research activities in this field, FBH achieves state-of-the-art results. The portfolio of normally-off power transistors realized so far ranges from devices with high current capability of 150 A optimized for 250 V bias to power transistors with 1200 V blocking voltage and 5 A maximum current.

Since GaN semiconductor epitaxial layers have already been demonstrated on up to 200 mm Si substrates, the excellent electronic properties of GaN devices can now be combined with stable and cost-efficient production processes of the silicon industry. It is therefore to be expected that the costs for GaN power transistors, in the medium run, can compete with those for sophisticated Si transistors.

P-GAN GATE TECHNOLOGY FOR NORMALLY-OFF GAN TRANSISTORS

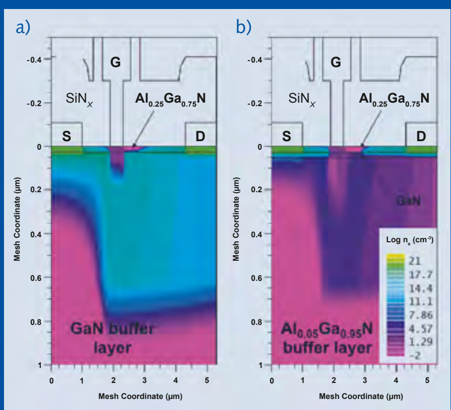
GaN HEMTs utilize a thin conductive layer at the interface between GaN buffer and AlGaN barrier as transistor channel. With increasing negative voltage at the metallic control electrode (gate) the channel depletes underneath the gate, the transistor starts to block the current. In p-GaN gate transistors, the gates of GaN HEMTs are replaced by p-type GaN semiconductor gates. Thus, a negatively charged depletion region arises which suppresses electrons in the transistor channel underneath the gate. This effect even appears without applying an external voltage (normally-off transistor). At a positive threshold voltage of around 1.5 V, the transistor channel starts to switch on and is fully unblocked (on-state) at approximately 5 V. When the transistor is switched on, electrons flow around 10–20 nm below the p-doped gate region without getting in contact with the acceptors. Consequently, full electron mobility within the channel can be preserved.



▲ *Conduction band distribution underneath a normally-off p-GaN gate (blue line, assembly: inset above) compared to a Schottky gate (red line, assembly: inset below)*

HIGH-VOLTAGE CONCEPTS FOR GAN POWER TRANSISTORS

The off-state breakdown voltage of GaN-based HEMTs is mainly determined by a sudden increase of the sub-threshold drain current. At high drain bias and under off-state conditions, electrons might leave the transistor channel by-passing the region controlled by the gate. This phenomenon is called "punch-through effect". To prevent electrons from drifting into the GaN buffer, a back barrier is mandatory. Due to polarization-induced p-type doping, an AlGaN buffer acts as back barrier and prevents electrons from punching through the buffer. Carbon-doping of the GaN buffer additionally creates acceptor-like trap states that scavenge any injected electrons. Transistors withstanding 190 V/µm field strength and blocking more than 1000 V have been realized at FBH with a carbon-doped GaN buffer as back barrier.



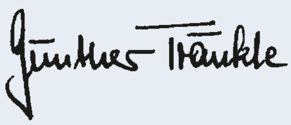
◀ *Simulation of electron concentration distribution in pinched-off GaN-HEMT device (a) with GaN buffer layer showing punch-through and (b) with back barrier layer with suppressed punch-through*

EDITORIAL

As a key technology, power electronics is cross-industrially used in a great variety of applications, ranging from automobile industry and industrial networks to power converters in solar plants and wind power stations. Due to reduced costs, improved reliability and higher power densities, the global demand for energy-saving power components based on gallium nitride increases. At FBH, we develop novel topologies and designs required to open up the performance potential of the material.

With our third **frequent** issue, we present our concepts and solutions for energy-efficient power components. We wish you an inspiring reading.

Yours



Günther Tränkle

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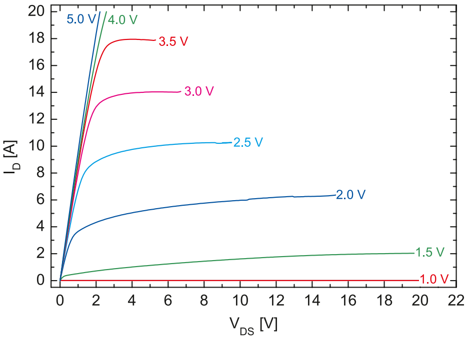
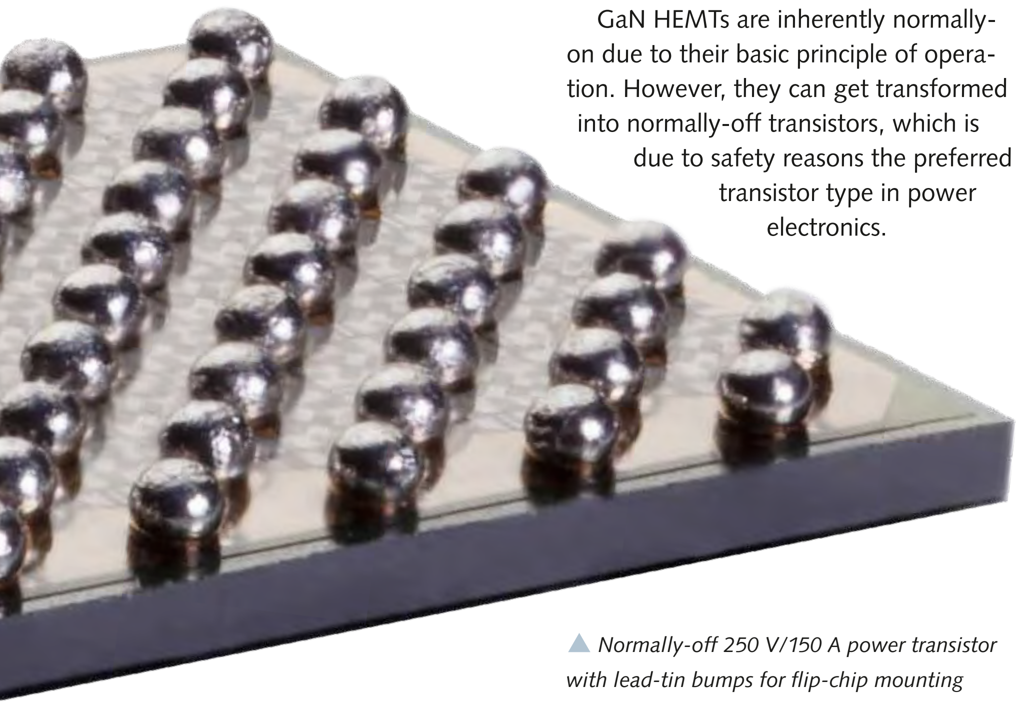
GaN high-voltage transistors for power electronics



Output characteristics of a normally-off GaN power transistor (250 V operating voltage, 85 mΩ on-state resistance)

Gallium nitride (GaN) is characterized by its excellent dielectric breakdown strength of 3.3 MV/cm—this value is approximately ten times higher than that of silicon (Si). Thus, with GaN-based power transistors significantly higher power densities and switching frequencies as compared to Si-based transistors can be achieved. High Electron Mobility Transistors (HEMTs) combine high electron mobility with high saturation velocity and are therefore well-suited for high frequencies and very fast switching applications. They consist of layers of various semiconductor materials with differently sized band gaps. In the case of GaN-based HEMTs, an AlGaN/GaN heterojunction induces a very conductive electron layer at the interface forming the channel in the transistor, the so called two-dimensional electron gas (2DEG). Consequently, unipolar devices with a particularly high proportion of breakdown strength to specific on-state resistance can be realized. Converter systems with GaN transistors benefit from high voltage operation, high current levels, and high switching frequencies up to the MHz range.

GaN HEMTs are inherently normally-on due to their basic principle of operation. However, they can get transformed into normally-off transistors, which is due to safety reasons the preferred transistor type in power electronics.



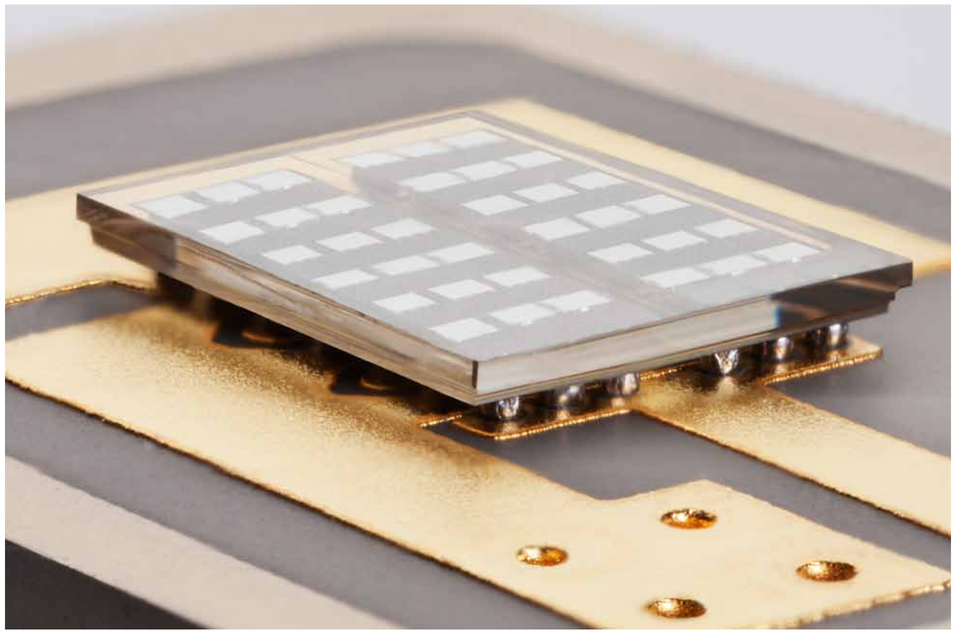
Normally-off 250 V/150 A power transistor with lead-tin bumps for flip-chip mounting

FBH's key R&D activities in this field:

- **Normally-off GaN transistors**
  For normally-off GaN power transistors, the FBH focuses on the p-GaN gate technology. By using this technology, an intrinsic potential distribution close to the gate is generated such that the devices can only be switched on at positive control voltage. A threshold voltage of around +1.5 V and a gate dynamic range in the region of +5 V are characteristic. Switching dynamics, in other words the difference between switched-on and switched-off voltage, is at least six orders of magnitude.
- **GaN transistors with 1000 V electric strength**
  By incorporating a back barrier into the GaN semiconductor layers, electrons can be concentrated within the channel even at high operation voltages. An electric breakdown strength above 150 V per µm gate drain distance is achieved. The specific on-state resistance of the 1000 V devices is reduced to < 1 mΩcm².
- **High-current transistors up to 150 A**
  A cellular transistor layout developed at FBH enables a simple two-dimensional scaling of the device size towards higher current levels. 150 A/250 V transistors have been realized for flip-chip mounting on a ceramic sub-mount with integrated high-current wiring.

The combination of these properties qualifies FBH transistors for power applications in automotive electronics, terrestrial and space-based solar converter technology and others.

Packaging of GaN power transistors

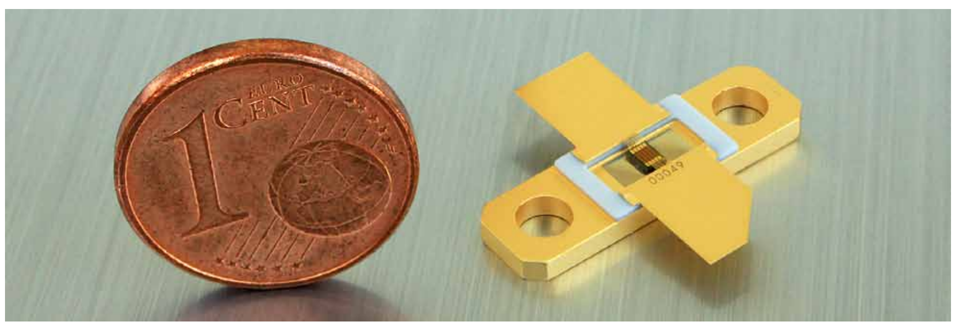


▲ *50 A GaN high-voltage power transistor chip with lead-tin bumps flip-chip mounted on thermally matched sub-mount*

GaN power transistors from the FBH are characterized by a fully lateral design. As all connecting pads are located at the front side of the chips, rather simple flip-chip mounting techniques can be applied. Compared to more conventional chip mounting methods, this technique leads to considerably smaller parasitic inductances, which is one of the prerequisites for fast and efficient switching.

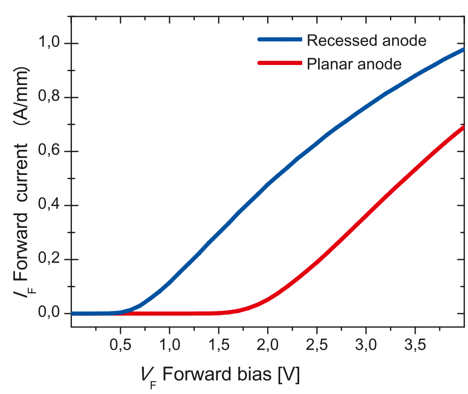
FBH has developed a technology for optimized heat dissipation from the active chip regions through the bumps to the heat-sink by automatically placing small metallic spheres (bump contacts) on the chips. A sophisticated annealing process is converting them into solder bumps. The present technology is optimized for lead-tin bumps, copper bumps ensuring a much better thermal conductivity are under development. As a matter of course, the power transistor process also allows conventional wire bonding techniques if requested. In addition to the lateral device concepts, FBH is currently developing GaN power devices utilizing a quasi vertical device architecture. This concept is ideally suited for heat dissipation to both sides of the chip and more efficiently utilizes active chip area. GaN high-voltage power transistors on silicon carbide substrates will be commercially available via FBH's spin-off company BeMiTec in 2012.

GaN-based Schottky diodes for efficient converter topologies



▲ *Packaged GaN Schottky diodes for 600 V, 1 A operation*

Wide band gap semiconductor material combinations like GaN/AlGaN-based heterojunction structures are of great interest for fast power switching diodes due to their properties such as very high breakdown strength at off-state and high conductance at on-state conditions. However, one of their main drawbacks is the high onset forward voltage—it increases the losses at on-state conditions. In this respect, Schottky barrier diodes with low onset forward bias combined with fast recovery time are favorable. The absence of a body diode in GaN HEMT high-power switching transistors calls for the development of high-performance diodes that may be used as free wheeling diodes in modern converter topologies. The electrical properties of these diodes such as blocking voltage and on-state resistance as well as the switching properties should be compatible to novel GaN-based high-power switching transistors in order to enable inherently efficient converter topologies. To meet these requirements, Schottky diodes with lateral device topology have been developed at FBH. These devices fully utilize the high channel conductivity provided by the 2-dimensional electron gas (2DEG) at the GaN/AlGaN heterojunction interface. They are characterized by a very low onset forward bias of 0.5 V combined with high blocking capability (V_{BR} > 1000 V), high switching speed and a very fast recovery time.

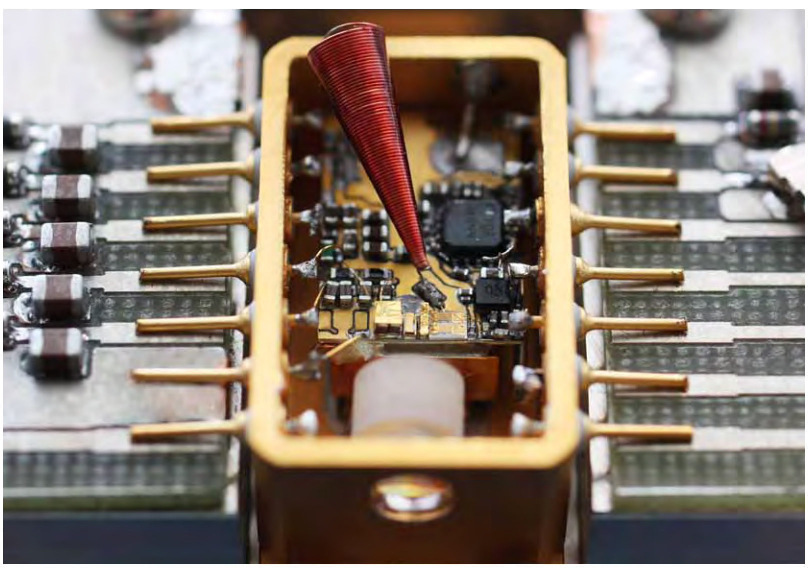


▲ *Typical characteristics of Schottky diodes with carbon-doped GaN buffer structure*

PRODUCTS IN FOCUS

Compact customized ns light pulse sources

For applications, such as in material and biological analysis, material processing, free-space communications and in metrology, FBH develops ns laser light sources with high output powers. For the first time worldwide, gain-switched 1064 nm DFB laser diodes with control electronics have been integrated into a butterfly housing. Thus, by mounting ultrafast GaN high-power transistors with corresponding driver adjacent to the laser, laser pulses from 1–10 ns with 2 W output power at a maximum pulse current of 3 A could be generated. Rise and decay time of the pulses are less than 0.5 ns. The beam is collimated by decoupling optics and the spectral width is smaller than 0.04 nm for the 1064 nm laser pulses. Within the housing, a Peltier element and a thermistor regulate the temperature.



▲ *Novel Laser source generates ns pulses with customized length and repetition rate*

Due to the specific mounting and the comprehensive circuit know-how, a very compact source has been developed generating customized ns pulse repetition in the range of 10 MHz up to single pulses. In addition, diode lasers of any desired wavelength can be mounted.

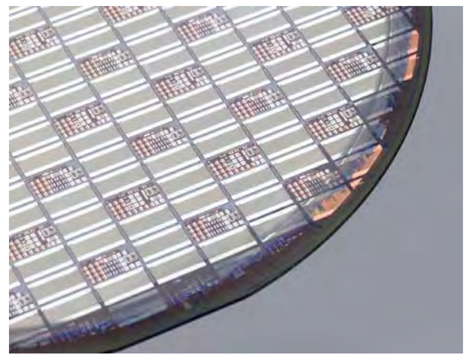
GaN-based microwave power transistors

There is a wide range of applications for discrete GaN microwave transistors operating at frequencies between 1 and 4 GHz, comprising communication systems as well as industrial generation of RF power. FBH develops and processes corresponding devices for RF power levels of 25 W, 50 W and 100 W per chip. Prominent criteria in this context are high efficiency and reproducibility. FBH fabricates the transistors on 4″ SiC substrates coated with epitaxial AlGaN/GaN functional layers. Product development and marketing of such microwave power devices is realized jointly by FBH and its spin-off company BeMiTec.

RESEARCH IN FOCUS

GaN HFETs with high current and high breakdown voltage

For power conversion, which is used, for example, in electric cars and photovoltaic systems, transistors with low on-state resistance and high voltage stability are required. GaN HFETs offer a particularly high potential for such applications. In order to increase their breakdown voltage, Fe- or C-doped GaN buffers can be used.

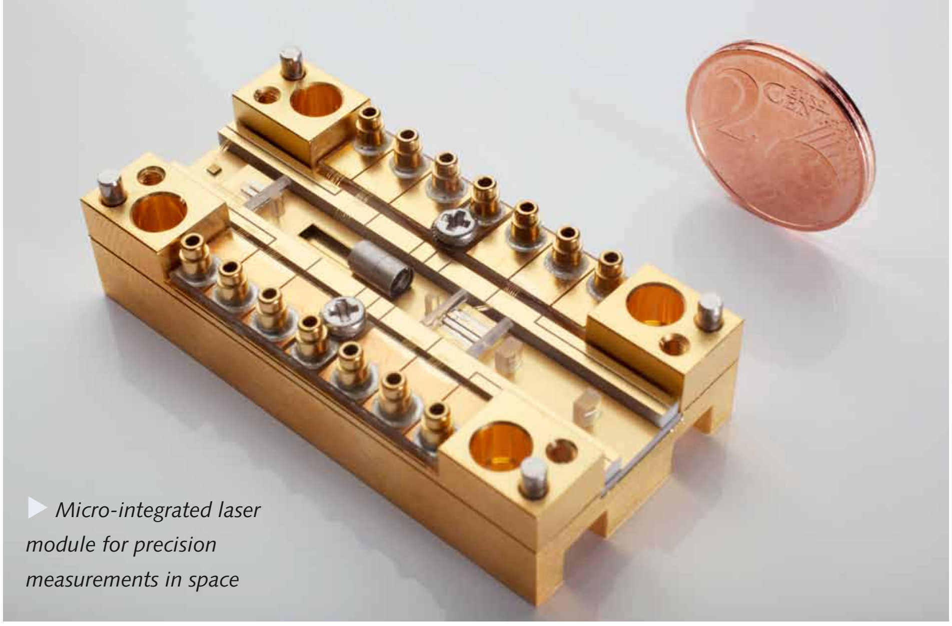


▲ *Normally-off high-voltage power transistors for 600 V operating voltage and 75 A peak current*

However, due to the higher barrier compared to undoped buffers, the carrier concentration within the channel decreases. The same applies for AlGaN buffers, which additionally increase the thermal resistance. This reduction of carrier concentration within the channel can be compensated by n-type doping of a thin (10 nm) AlGaN back barrier between C-doped buffer and channel layer. The electrons supplied from this layer result in a nearly doubled current $I_{ds,max}$ compared to an otherwise identical transistor structure. At the same time, voltage stability is not compromised and leakage currents remain low up to the measurement limit of 1000 V. Thus, such a thin n-doped AlGaN layer under the channel can significantly improve the trade-off between on-state resistance and breakdown voltage of GaN HFETs for power switching applications.

780 nm modules for precision measurements in space

The Laser Metrology group at FBH develops micro-integrated laser modules specifically suited for precision measurements in space. Significant efforts are currently set on the development of laser modules for precision spectroscopy applications on board of a sounding rocket taking off in 2013. Medium-term perspective is to install these modules on board of the ISS or within a dedicated satellite mission. The laser module concept relies on micro integration of laser chips, optical components, and electronics. Mounting is carried out on a common AlN micro-bench so that volume and weight are reduced by a factor of a few 100 compared to commercially available systems. The laser modules feature an outstanding spectral short-term stability (few kHz linewidth) at a power level of 1 W and more. They have successfully passed mechanical vibration and shock tests required for space applications. All assembly technologies applied and components used are or can be space qualified. FBH currently develops a space-qualifiable packaging concept including fiber coupling on the micro-bench. Although this development addresses 780 nm, the concept can be easily transferred to other wavelengths from 650 nm to 1100 nm.



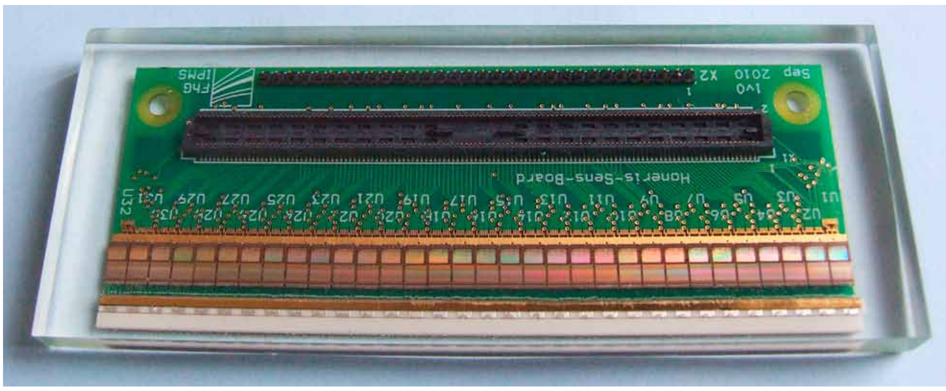
Micro-integrated laser module for precision measurements in space

Line sensors for novel X-ray detectors

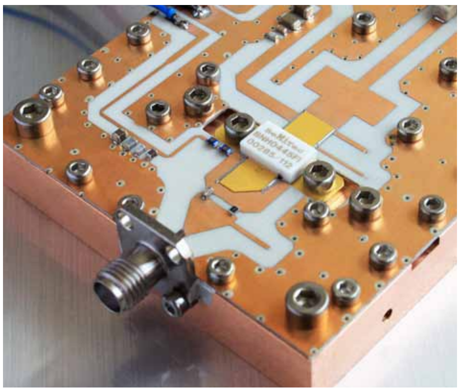
The FBH develops line sensors for innovative X-ray detectors in close cooperation with the Electronics Packaging Laboratory (IAVT) at TU Dresden. Only recently, novel direct-converting line detectors have been demonstrated. These devices resolve the disadvantages of present sensor systems comprising scintillator and photo detector. Key benefits are very low crosstalk between adjoining pixels, simple construction and expanded lifetime of the detector chips. Within the system, GaAs sensors directly convert X-ray photons into charge carriers with a lateral resolution of 100 µm per pixel. The demonstrator comprises a sensor with 1024 pixels and has been set up with assemblies for amplifier and evaluation electronics developed by the Fraunhofer institutes IZFP and IPMS.

Highly efficient power amplifiers and oscillators

In the framework of the regional growth core "Berlin WideBaSe", FBH and the regional SMEs BeMiTec, GloMic and Sentech joined forces to develop and market highly efficient microwave power amplifiers and oscillators. The focus is on technological concepts and circuit topologies towards highly efficient microwave amplifiers. Demonstrators are realized at two different frequencies. At 80 MHz, the desired power levels are 1 kW with 70% efficiency and accordingly 200 W with 60% efficiency at 2.45 GHz. These novel and highly efficient amplifiers will then be utilized for high-density plasma generation in plasma sources designed and fabricated by Sentech. Subsequently, the respective know-how gained during the project shall be marketed by the contributing companies.



Direct-converting line sensor with 1024 pixels and 100 µm lateral resolution



Highly efficient 30 Watt amplifier at 2.45 GHz

Leibniz Ferdinand-Braun-Institut

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 systems. Applications range from medical technology, high-precision metrology and sensors to optical communications in space. In the field of microwaves, FBH develops high-efficiency multi-functional power amplifiers and millimeter wave frontends targeting energy-efficient mobile communications as well as car safety systems. In addition, compact atmospheric microwave plasma sources that operate with economic low-voltage drivers are fabricated for use in a variety of applications, such as the treatment of skin diseases.

The FBH is a competence center for III-V compound semiconductors and has a strong international reputation. FBH competence covers the full range of capabilities, from design to fabrication to device characterization.

In close cooperation with industry, its research results lead to cutting-edge products. The institute also successfully turns innovative product ideas into spin-off companies. Thus, working in strategic partnerships with industry, FBH assures Germany's technological excellence in microwave and optoelectronic research.

The Ferdinand-Braun-Institut develops high-value products and services for its partners in the research community and industry which are tailored precisely to fit individual needs. The institute offers its international customer base complete solutions and know-how as a one-stop agency—from design to ready-to-ship modules.

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