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Next-Generation Wireless Communications

Making the Infrastructure Hardware Ready for 5G

- Towards the digital base station transmitter
- Boosting energy efficiency for wideband systems
- Dedicated semiconductor technology & measurement facilities

Wireless communications – making the hardware ready for 5G!

Wireless communications is part of everybody's daily life – privately and professionally. Continuous developments of the technology have facilitated an ever growing quantity and quality of services. While the recent advances were more of an evolutionary nature, the next generation ahead, referred to as 5G, promises quantum leaps in three dimensions: highest data rates, extremely low latency along with maximum reliability, and countless numbers of connected devices.

This new standard will not only boost consumer's experience, but also bring in completely new fields of applications: It forms the basis for the mega topics Internet of Things and the German Industrie 4.0 program (enhancing automation and network functions in manufacturing technologies) as well as autonomous driving.

Ambitious agenda with demanding technical requirements

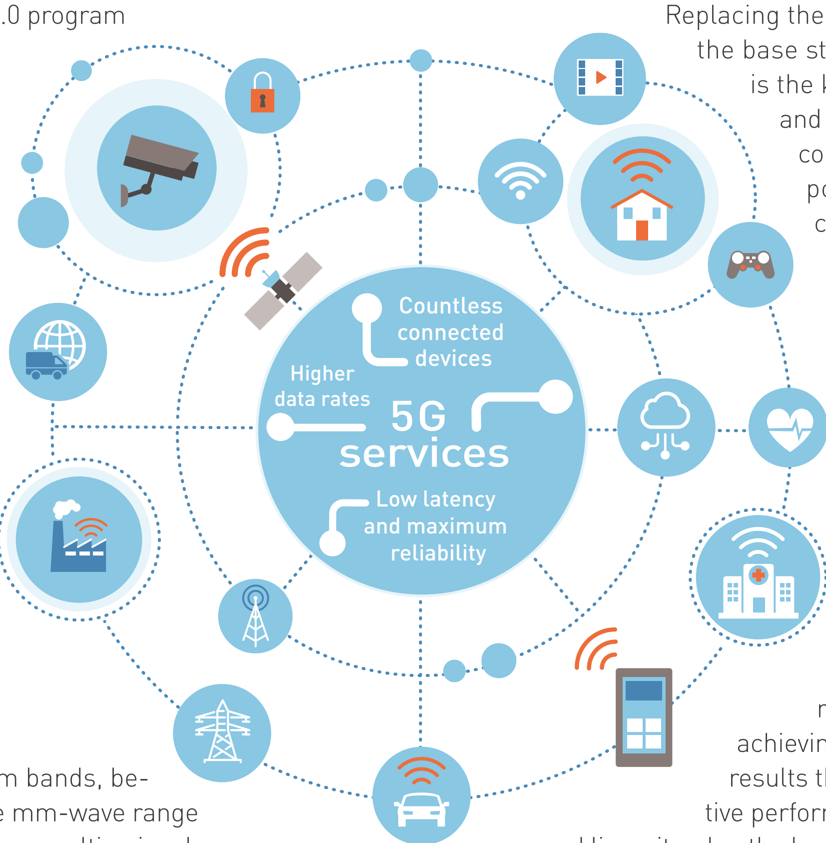
Target numbers on the various features have already been published, but how to accomplish them technically is still under debate. However, it is clear that 5G requires comprehensive innovations on the side of the hardware components:

- Extension to new spectrum bands, below 6 GHz as well as in the mm-wave range
- Ultra-dense radio networks, resulting in a huge increase of base stations or equivalent nodes
- More flexible air interfaces, i.e., radio frontends
- Introducing massive MIMO (multiple-input multiple-output) approaches to enhance spatial diversity

All this is to be achieved at a lower power consumption of the network and thus at improved power efficiency, particularly on the base station side. And the roadmap is ambitious; the first systems are scheduled to be deployed in 2020. The technical challenges behind these targets are manifold. The usage of mm-wave bands for mobile communication scenarios alone comprises a bunch of critical issues to be solved. It ranges from the propagation phenomena, which differ completely from the common 2 GHz situation, to the required cost- and power-effective radio transceivers for the infrastructure. They need to offer sufficient output power to reach reasonable cell coverage and easy integration into multi-antenna systems. The high number of base stations and the multitude of services to be offered demand for generic elementary hardware components which can be employed for various frequency bands and transmission schemes. Even more desirable are reconfigurable building blocks that can be controlled by software and allow flexible usage, the next step on the path towards software-defined radio.

How FBH is addressing the 5G challenges

(i) The need for versatile hardware components can be met by increasing the digital contents in the radio frontend. Replacing the microwave transmitter in the base stations by a digital version is the key step in this direction – and a disruptive one since all conventional microwave power amplifier (PA) concepts are still analog. This turns the linear PA into a high-speed high-power switch, signals have to be studied in time rather than in frequency domain. FBH has been focusing on this topic for some years, covering the entire chain with encoder and modulation scheme, GaN switch amplifier, and output filter. Significant progress has been made, achieving internationally leading results that demonstrate competitive performance regarding efficiency and linearity, plus the benefits of the digital concept.



(ii) The ultra-high data rates promised by 5G – ten to one hundred times of what LTE offers presently – can only be reached with a combination of dedicated modulation schemes and high bandwidth. The advanced modulation schemes lead to a high peak-to-average power ratio, which greatly compromises PA efficiency and thus power consumption of the entire infrastructure. At the same time, wide bandwidth brings conventional PA concepts to their limits. FBH is working on this Gordian knot and has shown best-in-class high-bandwidth high-efficiency solutions based on a discrete envelope tracking approach.

(iii) 5G-related advances in hardware rely on improvements in semiconductor technologies as well as in design and characterization methods. Thus, FBH's GaN and InP processes along with its design and measurement capabilities are key to success.

Editorial

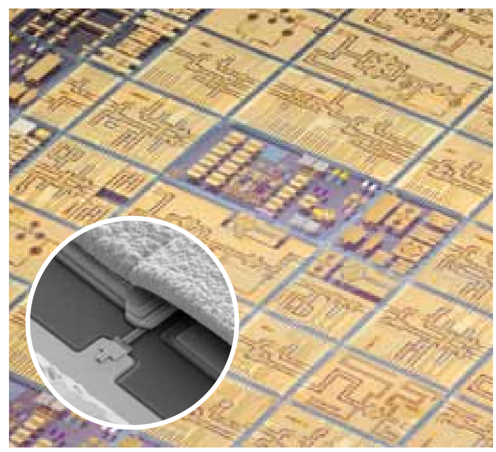
Next-generation mobile standard 5G promises a quantum leap in wireless communications, envisioning a hyperconnected society. Consumers may soon enjoy interactive and ultra-HD videos from 360-degree cameras transmitted over a 5G system to virtual reality glasses. Businesses will be enhanced with automation, better logistics, and coordination – anything of value will be connected and tracked. Machines, for example, are expected to predict failures and trigger maintenance processes autonomously. Health shall be real-time monitored in the future, and an operation could even be performed by a robot remotely controlled by a surgeon located on the other side of the world. In our current frequent issue, we have compiled FBH research results, contributing to make the infrastructure hardware ready for 5G. I wish you an inspiring reading!

Yours sincerely,
Günther Tränkle

Günther Tränkle

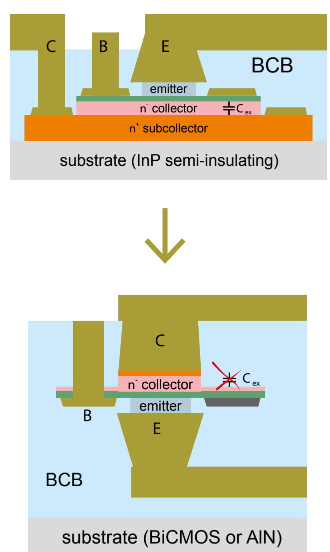
GaN HEMT technology – the baseline for high-power high-speed components

Gallium nitride (GaN) transistors are the technology of choice if both high output power and efficiency at frequencies up to W-band are needed, as required for the 5G infrastructure. This makes them the ideal candidates for efficient power amplifiers from a few GHz to mm-waves around 60 GHz and more. FBH´s GaN technology for microwave devices relies on a well-established 4-inch GaN-on-SiC process with a high degree of repeatability and reliability. Three process options optimized for S-band discrete devices, X- and Ka-band MMICs deliver state-of-the-art results. They are composed of standardized process modules and mainly differ in terms of the transistor cells' gate lengths, being 0.5 µm for S-band devices, 0.25 µm for X-band MMICs, and 0.15 µm for Ka-band MMICs. The active GaN devices benefit from FBH´s newly developed Ir sputter gate technology giving rise to extremely low failure rates and significantly reduced dispersive effects.



InP heterobipolar transistors – device technology for switch-mode mm-wave power amplifiers

Indium phosphide heterobipolar transistors (InP HBTs) are well suited for switching power-amplifier applications at mm-wave system frequencies in W-band and beyond, owed to their unique combination of high electron speed and high electric breakdown field along with the high current-to-capacitance ratio in their vertical architecture. This enables power amplification up to 1 THz when scaling the emitter width accordingly. In FBH's InP HBT process, the collector capacitance is drastically reduced in a wafer bonding process, allowing to replace extrinsic collector semiconductor material by a low-k dielectric. Therefore these devices are particularly well adapted to switch-mode operation, with the baseline 800 nm technology exhibiting a collector breakdown voltage above 4 V and cutoff frequencies around 350 GHz with only 8 fF base-collector capacitance.



Promoting the digital era – components for a digital transmitter architecture

Next-generation wireless communication infrastructure demands for high flexibility, low cost, and high efficiency. These requirements are complemented by the growing need towards better coverage within a cell as well as wideband, multi-band, and multi-standard features. As RF power amplifiers (PAs) are the last analog part in the base station transmitter chain, making also the RF PA digital is the logical next step. At the same time, it represents the most advanced solution to serve these purposes.

Looking at the functional details: The digital baseband is first fed into a modulator that converts the signal into a single-bit bit-stream, i.e., a binary pulse train, which is suitable to be amplified by the digital PA. After the PA, the analog transmit signal is restored by a band-pass filter. At FBH, all three parts of such a digital transmit chain (modulator, PA, filter; see Fig. 1) are the subject of intensive research.

The modulator is an essential component since its capabilities directly define the quality of the restored signal; it has significant influence on the actual efficiency of the PA as well.

A new modulator concept developed at FBH (Fig. 2, pending patent) not only improves the signal quality compared to already existing modulators, it also features the ability to correct the most dominant amplifier distortions without further efforts. It therefore reduces the requirements for a power-hungry and complex digital pre-distortion or even renders it superfluous. The modulation can be adapted to the abilities of the pulse forming hardware in an actual implementation and can be tailored to the specific properties of the PA. For example, a 5 MHz WCDMA signal with 6.5 dB peak-to-average power-ratio (PAPR) encoded at 900 MHz exhibits highest adjacent channel leakage ratio (ACLR) values of more than 57 dB and an error-vector magnitude (EVM) of 1 % only. Moreover, the spectral purity and properties of the novel modulation scheme distinctly relaxes the specifications on the output filter so that simpler band-pass realizations can be used.

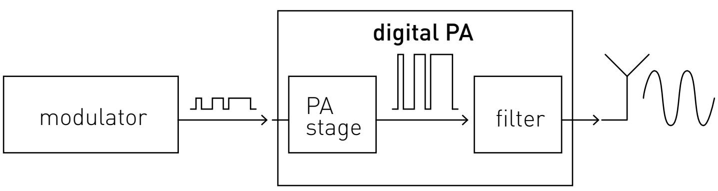


Fig. 1. Digital transmitter architecture including modulator, PA stage, and filter.

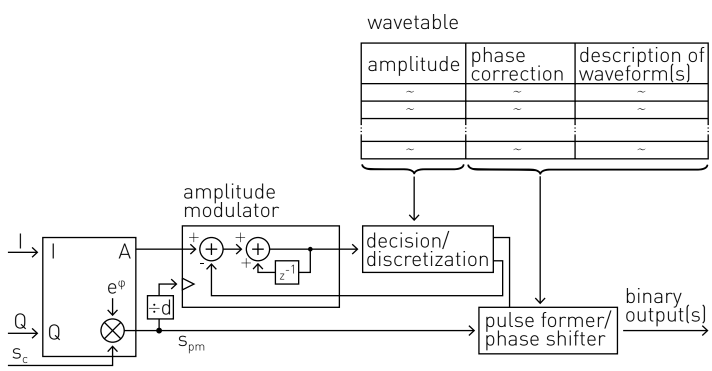


Fig. 2. Wavetable-based digital modulator.

Challenging the analog world

Recently, the digital PAs developed by FBH (see Fig. 3) reached competitiveness with common analog concepts like Doherty in terms of overall efficiency (PAE) and linearity. Applying improved driver circuitries such as push-pull gate driving together with zero-voltage switching techniques leads to a high overall PAE of more than 40 % within a 10 dB PAPR range in the 1 GHz region. Excellent linear behavior of the digital designs has been proven, reaching 50 dB ACLR and 1 % EVM.

Further alternative concepts to improve efficiency are pursued and tested. Energy recovery appears to be one promising approach in this regard: The out-of-band energy at the output of the digital PA is converted to DC by using a suitable rectifier circuit. The gained power assists in supplying the PA, which significantly enhances the efficiency by up to 15 %.

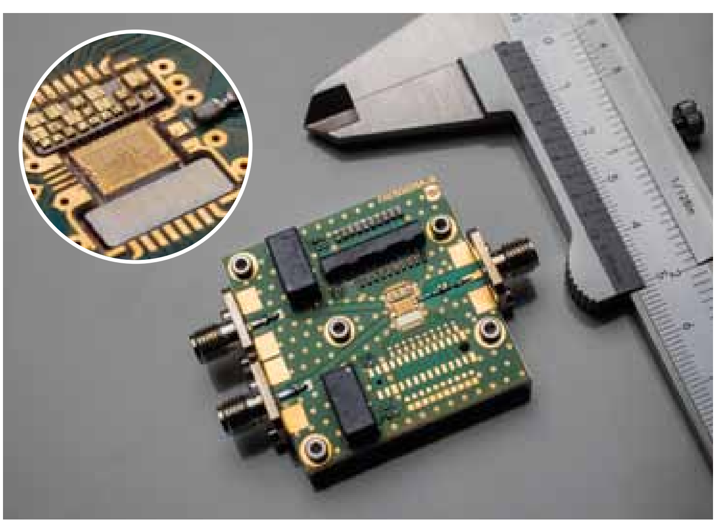


Fig. 3. Novel digital power amplifier module including output filter.

For a green future – boosting energy efficiency for wideband systems

Increasing the bandwidth and thus data rate while maintaining the efficiency of power amplifiers is a key challenge when heading towards 5G. Among the various approaches to accomplish these goals, discrete level envelope tracking (ET), which is also known as class-G, has lately emerged as one of the most promising candidates. Advances in this field are much accredited to work conducted in FBH's RF Power Lab in cooperation with University of Stuttgart. All aspects of discrete ET have been investigated: transistor optimization, modulator design, PA design as well as system optimization and linearization.

Basically, in discrete ET the supply voltage is modulated in discrete steps according to the instantaneous envelope of the signal as shown in Fig. 1. Hence, the dissipated power is reduced, but the transient shift of supply voltage introduces discontinuities in the output signal. The modulator is merely a very fast switch that selects the supply voltage from a limited number of available fixed voltages.

Beyond state-of-the-art for wideband operation

The FBH solution uses the same 0.5 µm gate length packaged RF power GaN technology both in the switch and in the RF power amplifier. Several designs with different numbers of discrete levels have been evaluated, improving the efficiency up to 19 % points for a wideband signal compared to single supply voltage operation. The possibility to linearize the transient discontinuities has also been shown by developing a novel predistorter model for digital predistortion (DPD) and in the analysis of a very wideband system with 75 MHz IQ bandwidth. Recent work demonstrates improvements over the state-of-the-art in extreme wideband operation. At present, the modulator switches up to 200 MHz with an estimated output power of 80 W in pulsed operation.

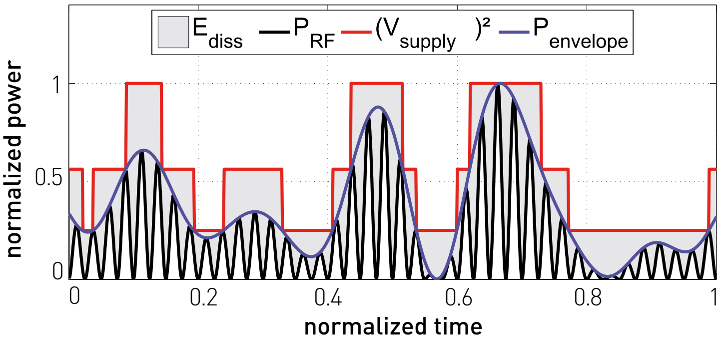


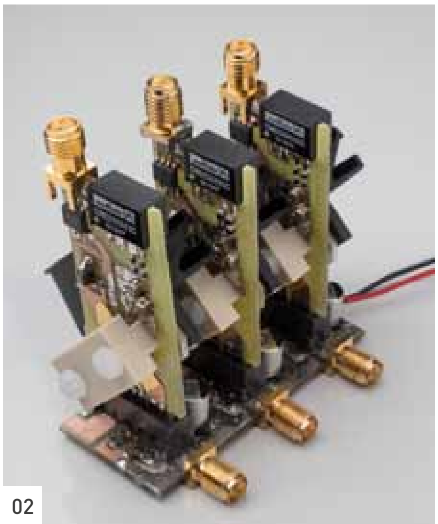
Fig. 1. Time domain waveforms of envelope and supply voltage showing the reduced losses for a discrete (class-G) modulated system.

In a three level class-G system operating in the 1.8 – 1.9 GHz band the average output power is 7 W with a 10.4 dB peak-to-average power ratio signal with 75 MHz IQ bandwidth. A level-adaptable multi-stage class-G modulator is shown in Fig. 2 and a full system including the RF power amplifier in Fig. 3.

For the continued work a new wideband PA characterization measurement system has been developed. RF signals up to 6 GHz with modulation bandwidths up to 1 GHz can be characterized in the fully automated MATLAB-controlled setup.

Class-G already shows competitive performance compared to more established efficiency enhancement topologies like Doherty, Outphasing, and continuous ET. Future work will include integrated solutions targeting future communication standards at higher frequencies. 5G is the buzzword, and class-G is the technology fulfilling the challenging demands of this new high-performance communication standard.

Fig. 2. Modular high-power modulator for multi-level class-G operation.
Fig. 3. Class-G discrete envelope tracking system.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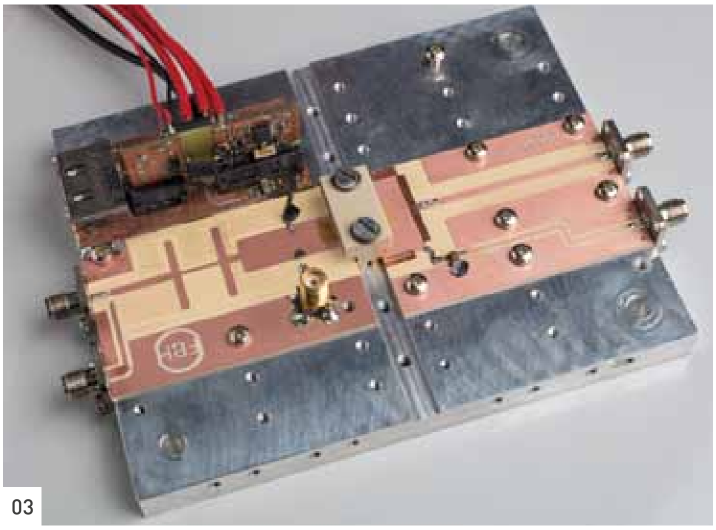
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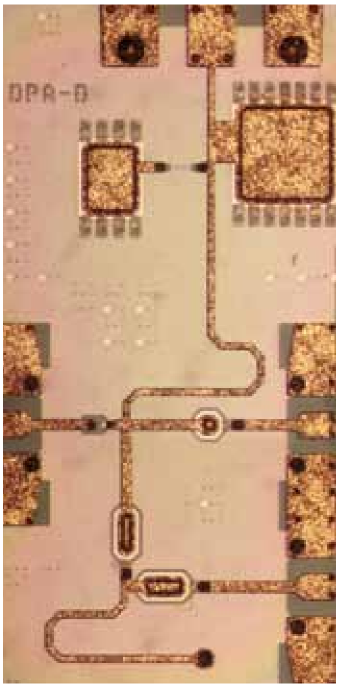
Pushing the frequency limits – digital power amplifiers for 100 GHz and beyond



100 GHz InP DHBT digital power amplifier MMIC.

Due to the ever increasing demand towards higher data rates and multiple wideband as well as multi-band features, future high-speed communication standards like 5G call for extreme signal bandwidths above 1 GHz and beyond. In this context, extending the spectrum into the mm-wave range is inevitable, and even frequencies in the sub-THz range (100 GHz – 500 GHz) are considered as an important step to cope with the challenges.

Common millimeter-wave power amplifiers (PA) apply analog design approaches like class A, AB, or even class-E. As these types of PAs are narrowband, and the transistors require a proper input as well as output matching, they are limited in terms of flexibility and compactness. To overcome these restrictions, FBH transferred the digital PA approach for the first time to the sub-THz region.

A highly efficient W-band amplifier was realized as MMIC with FBH's 0.8 µm InP DHBT transferred-substrate process. It utilizes a double-emitter-finger unit cell with an area of 2 x (0.8 x 6) μm^2 and includes a band-pass filter at the output with 0.6 dB insertion loss at 95 GHz signal frequency. Moreover, it does not use any special reactive matching which saves area and thus cost. Due to the flexibility of the approach the MMIC PAs can be used and combined for different concepts and signal frequencies, respectively. One only has to adapt the output filter network. A peak overall efficiency (PAE) of 31 % and collector efficiencies of more than 80 % demonstrate the great potential for future high-speed high-bandwidth communications.

Verification is crucial – measurement technology for power transistors

In the development of microwave power transistors it is very important to obtain first information on their performance under application-like conditions at an early stage in the design cycle. The new generation of GaN devices targets frequencies up to 50 GHz for space and 5G communications. These are also the frequencies addressed by the new load-pull measurement systems that have been set up at FBH. Besides classical on-wafer load-pull they provide waveform measurements with up to 4 harmonics at X-band. The lower band system up to 34 GHz can handle up to 20 W and the full 8 GHz to 50 GHz system 10 W. Modern pre-matching tuners and optimized on-wafer probers provide an exceptional passive matching range with $\Gamma > 0.82$ at 20 GHz and an expected $\Gamma > 0.70$ for all frequencies at the probe-tips.

Another versatile tool is the pulsed S-parameter system, enabling to characterize S-parameters in very short pulses below 200 ns pulse width. This allows nearly isothermal characterization under controlled conditions for the traps in the device. The transistor is biased in a quiescent point (Q-point) at a certain pre-condition for the traps and then shifted very fast to another operating point where the S-parameters are measured. Ideally, the traps are too slow and maintain the state of the Q-point. Measurements are conducted in a system that can handle the full power of individual cells on-wafer. S-parameters are characterized in the 400 MHz to 40 GHz range.

20 W load-pull system for device characterization up to 34 GHz.

Product in focus

Advanced kilowatt-class diode laser bars for pump applications

Diode laser bars with 1 cm aperture are deployed in high volumes in industrial and scientific applications and continuously improved performance is required. Recent research at the FBH into such bars has increased both optical output power to around 1 kW and conversion efficiency at high output to around 50 … 70 %, for use in a range of pump applications. The understanding obtained and technology developed has allowed the FBH to offer solutions tailor-made to address challenges in various commercial applications. For example, ongoing FBH design and technology developments have enabled kW-class bars to be made available that deliver peak performance in multiple different applications in the pumping of solid-state lasers, from established solid-state amplifier materials (Nd:YAG or Yb:YAG crystals) to alternative materials (Yb:CaF_2), for short pulse (100 µs), long pulse (2 ms) and continuous wave pump applications. Cooperation partners span from high technology SMEs, to large concerns. Exemplary results include demonstrations of 1 kW per bar in CW mode (15°C), 2 kW per bar in QCW mode (200 µs, 200 K), and long-pulse (2 ms) passively cooled stacks with high spatial brightness and conversion efficiency of 3.7 MW/cm^2-sr and 57 % respectively.

Kilowatt-class bar mounted on low-resistance conductively-cooled heatsink.

Research in focus

Pushing micro and nanoelectronics – FBH is part of Forschungsfabrik Mikroelektronik Deutschland

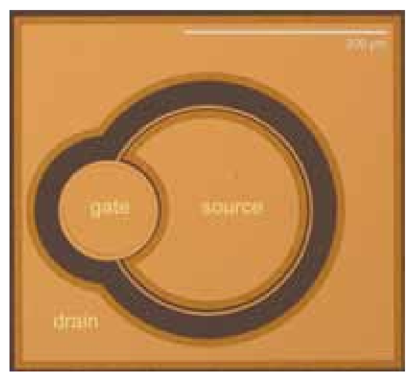
In April 2017, Forschungsfabrik Mikroelektronik Deutschland was launched, funded by the Federal Ministry of Education and Research with up to 400 Mio. Euros over the next 3.5 years. This initiative aims to boost German developments in micro and nanoelectronics, thus providing the technological basis for future applications in production, energy, mobility as well as in communications. FBH is a partner in this cross-institutional cooperation of Fraunhofer Group for Microelectronics and Leibniz institutes FBH and IHP, aiming to prevail in a competitive global market with advanced German R&D products.

First Bose-Einstein condensate in space – FBH contributes with capable laser modules

For the first time ever, a Bose-Einstein condensate has been successfully created in space in January 2017. The MAIUS mission demonstrated that quantum optical devices can be operated even in such harsh environments – a prerequisite for finding answers to the most challenging questions of fundamental physics and an important innovation driver for everyday applications. A compact and robust diode laser system for laser cooling and atom interferometry with ultracold rubidium atoms was developed. Core components were four hybrid-integrated master-oscillator power-amplifier laser modules developed by FBH, delivering spectrally pure and highly stable optical radiation.

Gallium oxide transistors for power electronics successfully demonstrated

FBH has successfully demonstrated metal-insulator-semiconductor field-effect transistors (MISFETs) based on gallium oxide (ß-Ga_2O_3), revealing the potential of this new material. By combining high-performance ß-Ga_2O_3 epitaxy with optimized processing and high-quality Al_2O_3 ALD gate insulator technology, state-of-the-art devices could be realized. Leibniz Institute for Crystal Growth provided the substrates and homoepitaxial n-doped layers. FBH took care of a dedicated transistor layout and developed specific technological steps for Ga_2O_3 transistor fabrication. Finally, competitive MIS transistors with drain current levels up to 85 mA/mm and a pinch-off voltage of -23 V have been demonstrated. They showed very low sub-threshold drain and gate currents of less than 10^{-10} A/mm. Thus, the transistors have demonstrated the suitability of this new material for devices offering outstandingly low leakage currents and huge $I_{ON/OFF}$ ratios of more than 10^9.



SEM viewgraph of a circular MISFET fabricated on n-doped gallium oxide.

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. 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 economic low-voltage drivers for use in a variety of applications.

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 through 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. Overall, working in strategic partnerships with industry, FBH ensures German 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. With its Prototype Engineering Lab, the institute additionally created an active interface between science and industry. By means of prototypes it turns excellent research results into market-oriented products, processes, and services. The institute thus 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,
Leibniz-Institut fuer
Hoechstfrequenztechnik
Gustav-Kirchhoff-Str. 4
12489 Berlin, Germany
Phone +49.30.6392-2626
www.fbh-berlin.com/frequent

Editors: Petra Immerz, Gisela Gurr

Layout: telegrafik berlin

Images:
icons made by: Gregor Cresnar, Madebyoliver, Zlatko Najdenovski, and plainicon from www.flaticon.com
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