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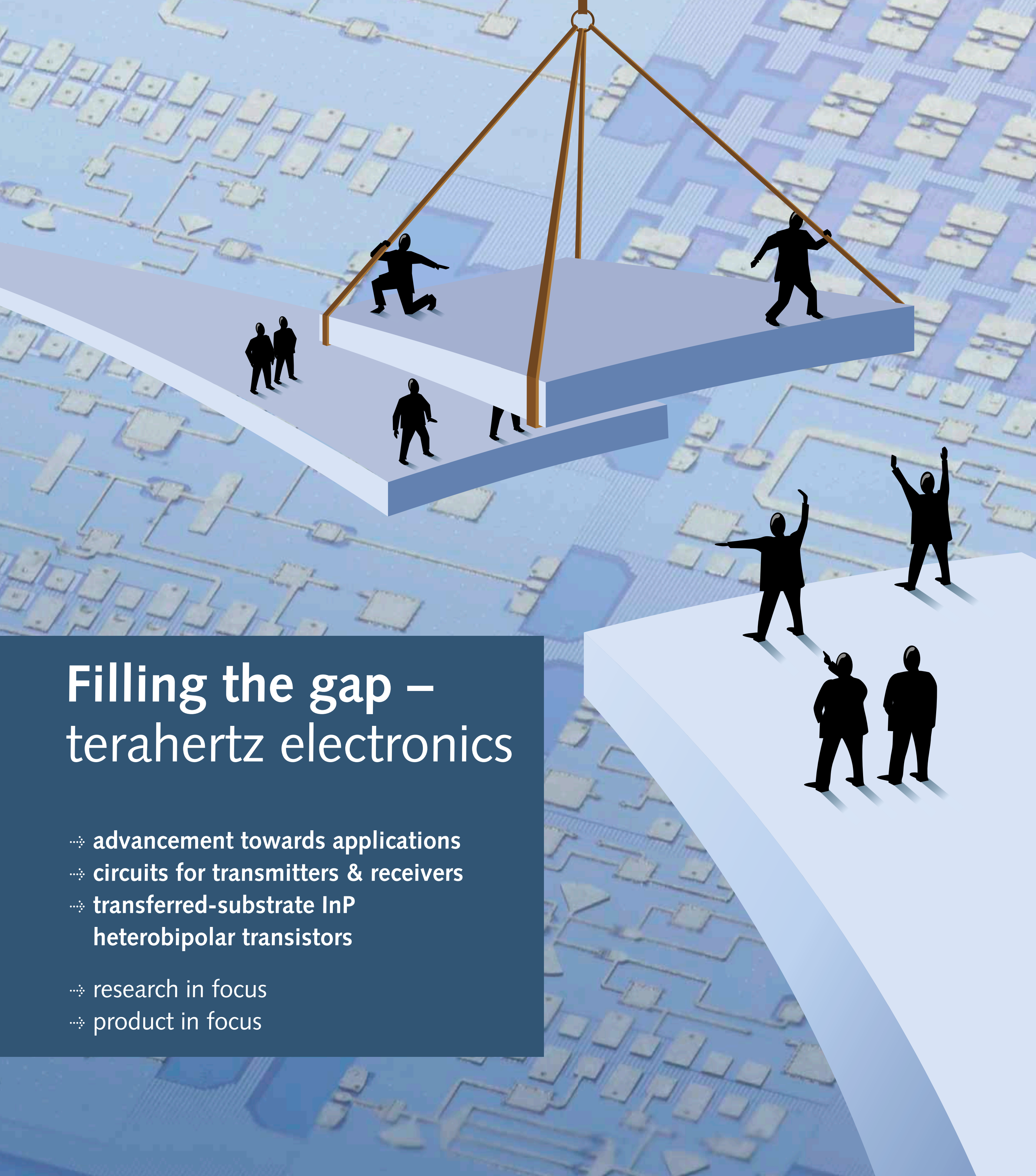
Research news from the Ferdinand-Braun-Institut

FBH



Filling the gap – terahertz electronics

- **advancement towards applications**
- **circuits for transmitters & receivers**
- **transferred-substrate InP heterobipolar transistors**

- research in focus
- product in focus

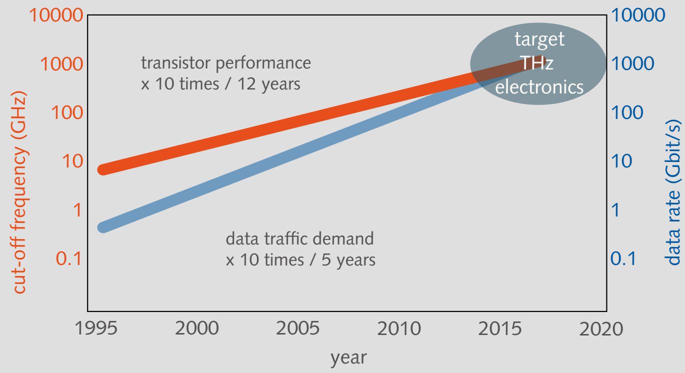
Terahertz electronics –
advancement towards applications

Faster, higher, more powerful, and strategically refined! Like in sports, electronics is driven by a public demand for faster communications, more powerful imaging modalities as well as complex and adaptive circuits and systems. Dedicated high-speed electronic technologies, complex system-on-chip solutions, and characterization facilities able to verify high-speed operation are essential for a leading position in this area. The Ferdinand-Braun-Institut (FBH) offers an excellent environment in this field and has additionally expanded its circuit technology facilities towards terahertz frequencies (THz).

The indium phosphide (InP) double heterojunction bipolar transistor (DHBT) transferred-substrate (TS) process, the InP-on-BiCMOS DHBT process, and the InP DHBT-TS-on-diamond process reach cut-off frequencies around 350 GHz today and are being extended to reach over 700 GHz soon. FBH has demonstrated mixed-signal non-linear active integrated circuits (MMIC) up to 300 GHz as building blocks for system-on-chip solutions, using heterogeneous integration with silicon and diamond materials. For frequencies beyond 1000 GHz, FBH also explores plasmonic operation and develops the related interconnect and calibration techniques scalable to these frequencies.

Bridging the gap between fundamental research and applications

The broad spectrum of FBH activities encompasses chip design and fabrication. This way, FBH both advances the field of THz electronics and supports industry in developing applications that require THz electronics. FBH is cooperating with a large number of partners from research and industry, including a joint laboratory with the Goethe University Frankfurt am Main and foundry activities with the Leibniz-Institut fuer innovative Mikroelektronik (IHP). These FBH activities aim at filling the gap between the ongoing fundamental research and application-driven demand for a mature and stable technology along with a reliable support chain.

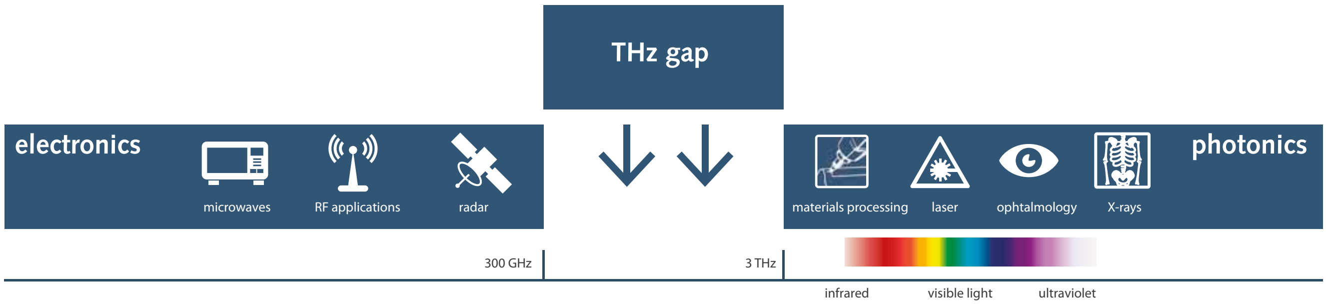


Demand and performance of electronic circuits

Terahertz electronics in a nutshell

Terahertz (THz) electronics is used to generate and detect THz radiation or to amplify signals in this frequency range. THz radiation is referred to as that part of the electromagnetic spectrum which lies between microwaves and infrared. Recently, the THz spectrum has become accessible with the push in high-speed operation of electronic devices and circuits towards the speed limit of electrons in semiconductors. Access to the THz range with optoelectronic devices requires a device operation regime where photon energies approach the thermal energy, which means operation at the noise limit.

THz radiation is non-ionizing and considered harmless, it can penetrate through non-metallic barriers and is therefore useful to detect hidden objects including subcutaneous tumors and packaged items. It can be used for stand-off detection of arts objects and compound materials. Thus, applications are versatile and range from medicine, security, and border check to non-destructive testing and material classification.



Editorial

Terahertz applications – filling the gap between electronics and optics

The terahertz frequency range represents the spectral region between electronic and photonic waves. Applications relying on the generation and detection of terahertz signals, such as terahertz imaging, high-resolution radar, high-speed communications, and spectroscopy are in need of electronic circuits operating in the frequency band between 300 GHz and 3 THz. Conventional semiconductor technologies cannot reach beyond 300 GHz, prompting the research and development of novel device and circuit concepts.

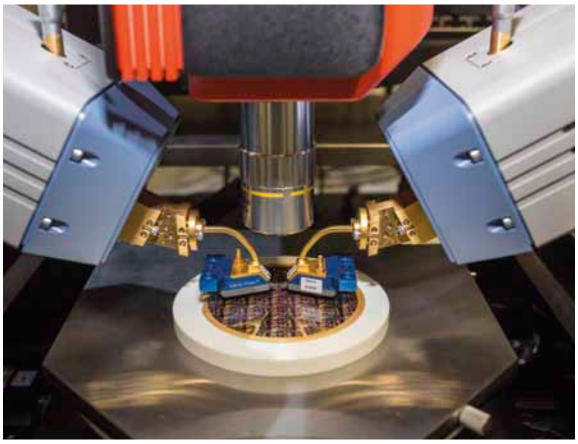
FBH is pursuing several activities aiming to advance terahertz electronics itself, while helping industrial partners to develop applications requiring terahertz electronic devices.

We wish you an inspiring reading of this frequent issue presenting insights and current FBH results in the field of terahertz electronics,

Günther Tränkle

Comprehensive electronic THz circuit characterization up to 1100 GHz

Electronic devices and circuits at THz frequencies can be tested at FBH using an automatized on-wafer measurement system up to 500 GHz (extendible to 1100 GHz). The equipment features precise semi-automatic probing (accuracy < 3 µm) and can map entire wafers without manual assistance. FBH develops low-loss interconnects (insertion loss < -0.5 dB @ 200 GHz) as well as calibration standards and methods with predictable performance up to 500 GHz. FBH also cooperates with NIST, PTB, and industrial partners on calibration hardware and software, leading to verifiable high-accuracy results. Key focus of these activities is to overcome the inherent multi-mode waveguide propagation along with radiation and coupling effects on wafers at frequencies above 100 GHz. FBH further operates a large-signal characterization setup for power amplifier and mixer characterization up to 750 GHz, currently being extended beyond 1100 GHz.



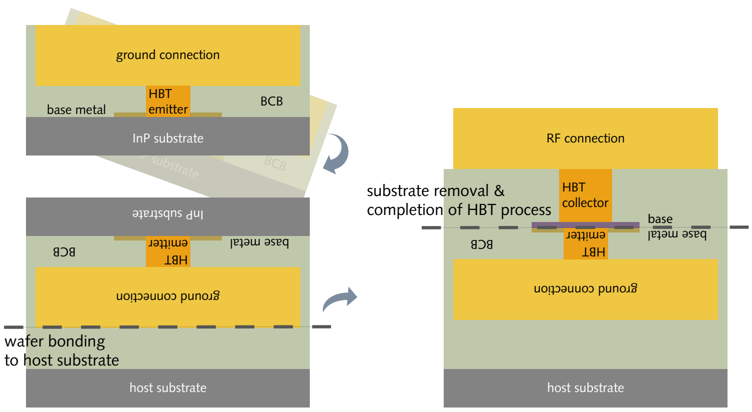
On-wafer THz measurement setup

Transferred-substrate process – pushing technological limits

Active semiconductor device layers are located on top of a substrate, which usually consists of the same material, to facilitate handling during processing steps. The close proximity of the substrate makes it an integral part of the device – worsening the device's high frequency properties through dielectric losses and fringing capacitances.

At FBH, the indium phosphide (InP) semiconductor substrate is removed following a wafer bonding process to a host substrate. A layer made of benzocyclobutene (BCB), a material with low dielectric constant and low loss tangent, is used as a wafer bond adhesive. This layer electrostatically separates the active device layers from the substrate. As a host substrate, low-loss aluminum nitride (AlN) is used for the highest-frequency InP HBT circuits.

The transferred-substrate process also works with fully processed BiCMOS wafers, in turn enabling InP-silicon heterointegration.



Schematic cross section of InP transferred-substrate process (only transistor is shown, drawing not to scale)

Building blocks for transmitter and receiver modules – circuits for THz frequencies

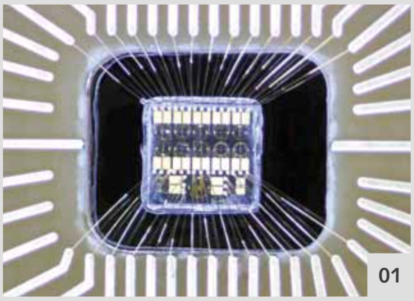
FBH offers several microwave monolithic integrated circuits (MMIC) technologies reaching cut-off frequencies above 300 GHz. MMIC design at FBH is based on a MMIC design kit with active and passive elements and proprietary large-signal HBT device models including thermal effects. Design kits exist for stand-alone processes and for the heterointegrated InP-on-BiCMOS process, SciFab.

InP HBT technology offers high voltage operation at high frequencies with excellent phase-noise properties. Therefore, FBH focuses on signal generation and amplification circuits. These circuits are building blocks for transmitter modules in THz systems. FBH has realized fundamental oscillator signal sources at 100 GHz, 200 GHz, and 300 GHz with measured output power > 0 dBm and good phase-noise properties. These sources are augmented by frequency multipliers at 164 GHz, 180 GHz (doublers) with P_{out} > 3 dBm, and at 240 GHz (tripler) with P_{out} > 0 dBm. FBH has also realized power amplifiers in the range of 48 - 180 GHz with P_{out} < 23 dBm and efficiencies > 20 %.

Novel approaches utilizing heterointegrated processes and plasmonic effects

Many of these MMICs have been combined with BiCMOS in a wafer-level heterointegrated process including an award winning InP-on-BiCMOS MMIC frequency doubler at 164 GHz and a tripler at 250 GHz (Best Paper Award EuMW 2013). Further circuits have been designed exceeding 600 GHz operation frequency.

FBH has further identified the region between 1 - 6 THz as particularly interesting for focal plane THz cameras and THz spectroscopy systems utilizing plasmonic operation of GaN HEMT MMIC detectors and signal sources in this frequency range. Arrays of such detectors for a focal plane THz camera operating in the frequency range 1 - 2 THz have been realized and exhibit state-of-the-art performance at 560 GHz.



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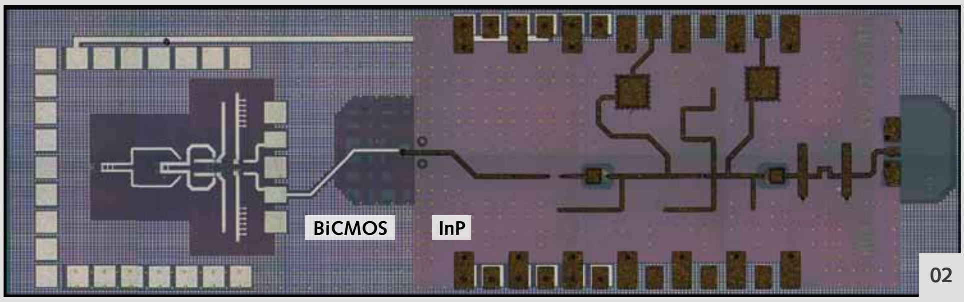
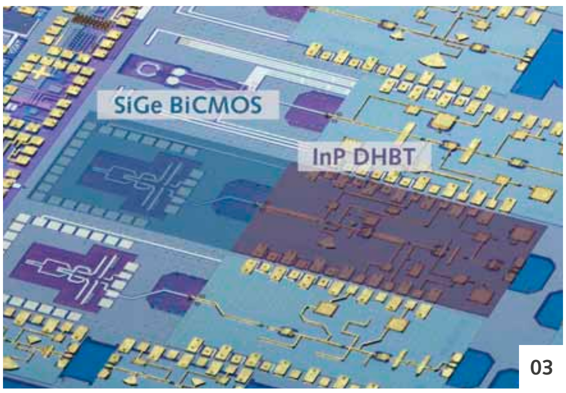


02

01 *Micrograph of MMIC array based on plasmonic GaN HEMT process to detect THz radiation*
02 *Merging the best of two technology worlds – combined InP-on-BiCMOS chip*

SciFab – monolithically integrated III/V-Si foundry process for mm-wave applications



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03 *Fully processed SciFab wafer with heterointegrated InP-on-BiCMOS chips*

The SciFab foundry process newly offered by FBH and IHP combines the advantages of two high-frequency semiconductor technology worlds in a unique heterogeneous wafer-level integration – high complexity BiCMOS (IHP) paired with high-power InP DHBT (FBH) technology. The wafer-level integration leads to a reduction in size, weight, and dissipated power as compared to existing assembly techniques.

The combined technology includes high-power InP DHBT devices with f_T & f_{max} above 320 GHz at 20 mA collector current and BV_{CEO} = 4 V breakdown voltage. Typical applications for this process are integrated mm- and sub-mm-wave RF sources. The SciFab library includes all necessary models and layout cells of transistors, capacitors, resistors, coils, interconnects, and line models.

www.ihp-microelectronics.com/scifab

Transferred-substrate InP heterobipolar transistors – the technology powering sub-terahertz electronic circuits

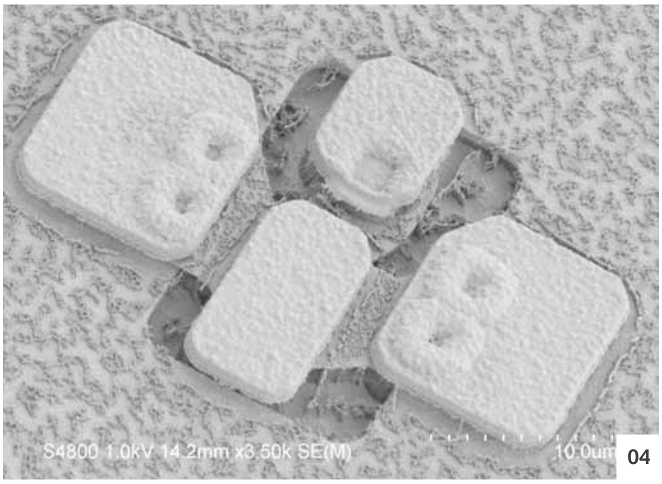
Indium phosphide (InP) heterobipolar transistors (HBT) are well suited for radio frequency (RF) power applications in the sub-THz region (100 - 1000 GHz) of the electromagnetic spectrum. Owing to the electronic properties of the InP semiconductor material, electrons are accelerated under an applied electric field more than three times faster than in silicon (Si), while the breakdown field in InP is 50 % higher compared to Si. For sub-THz operation, besides electrons having a short travel time through the transistor structure, the device cross-section area needs to be minimized in order to suppress unwanted parasitic capacitances. FBH's fabrication process results in reduced parasitic capacitances through exposure of the collector side and InP wafer removal, allowing for the definition of very small area collectors as compared to the usual top-to-bottom processing. InP HBTs fabricated in FBH's process with an emitter size of 0.8 x 5 μm^2 exhibit current gain and unilateral power gain cut-off frequencies (f_t and f_{max}) of around 350 GHz at 20 mA collector DC current. The RF output power per emitter area amounts to 6500 W/mm^2 at 96 GHz. The circuit integration includes three gold interconnect layers embedded in low-k benzocyclobutene. RF connections are designed as microstrip waveguides, displaying low loss up to 300 GHz.

Heterointegration of InP HBT onto SiGe BiCMOS wafers

In FBH's process, the active InP layers can be transferred to any suitable host substrate including fully processed silicon wafers. In collaboration with the research partner IHP, FBH has developed a wafer-scale process which monolithically integrates InP HBT, SiGe HBT, and CMOS devices. IHP's high performance 0.25 µm SiGe BiCMOS MMIC process (SG25H1) includes HBT transistors with f_T & f_{max} of 180/220 GHz and digital circuits with millions of CMOS transistors. Within the joint SciFab project it is used as substrate for combined MMICs. This technology is geared towards the realization of complex sub-mm-wave RF sources, offering reduced weight, size, and cost as compared to other module assembly techniques. The SciFab process is now open to external customers in a foundry mode.

Current research

Transistor cut-off frequency can be increased when reducing device dimensions. FBH is now introducing electron beam lithography to define the critical layers emitter, base, and collector. First transistors with 0.4 µm and 0.2 µm wide emitters are operational. With optimized dopant profile it is expected to reach an f_{max} of 700 GHz. In FBH's process, the InP HBTs are embedded in BCB without thermal substrate connection, resulting in only moderate thermal device impedance (R_{th} = 3000 K/W). A 10 µm thick nanocrystalline (NC) diamond heat sinking layer is added on top of the layer stack in an additional wafer bonding step. With thin-film NC-diamond exhibiting high thermal conductivity (400 W m^{-1} K^{-1}) and a very low loss tangent (< 10^{-4}) FBH has reduced the HBT's R_{th} by at least a factor of two without incurring additional RF losses.



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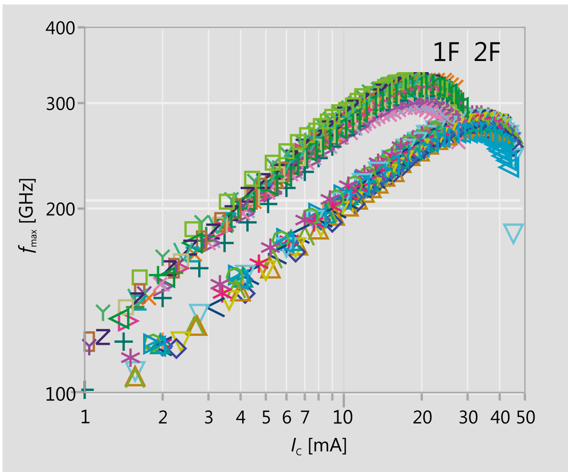
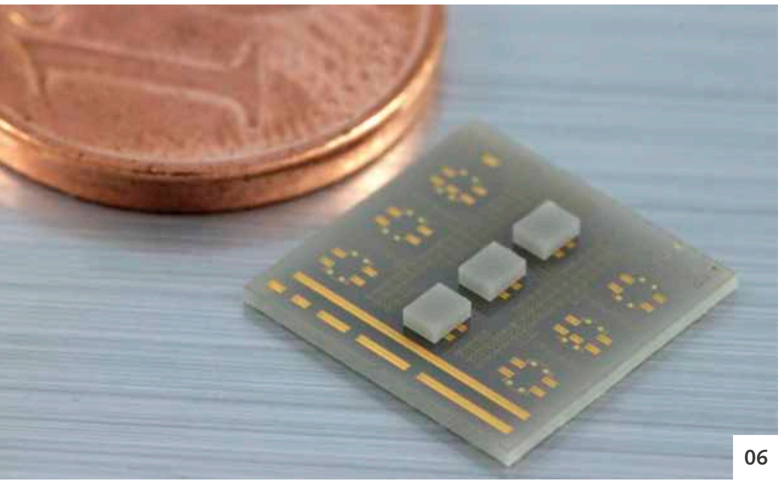


04 *Common base – InP HBT processed at FBH*
05 *f_{max} wafer lot overlay plot of single (1F) and two-finger (2F) InP DHBT heterointegrated with BiCMOS*

Flip-chip – a promising mounting technology for THz applications

Flip-chip connections offer shorter interconnection paths as compared to wire bonding, thus enabling higher bandwidth. The use of front-end semiconductor fabrication techniques allows for the accurate definition of thin-film waveguide structures leading to the flip-chip connection, resulting in predictable EM behavior up to 500 GHz. Recently, FBH has successfully developed flip-chip mounts operating up to 250 GHz, including a stripline-to-coplanar waveguide RF transition. The on-chip RF connections were realized as gold (Au)/benzocyclobutene (BCB) stripline waveguides, with an approximately 10 µm wide Au signal line sandwiched between top and bottom Au ground planes. BCB was used as a low-k interlayer dielectric.

The aluminum nitride submount featured gold-plated coplanar waveguides; interconnecting structures were realized with 10 µm diameter AuSn microbumps consisting of a multilayer metal stack with eutectic $Au_{80}Sn_{20}$ composition. Finally, the chips were placed onto the submount with the help of a semiautomatic flip-chip aligner with ±1 µm lateral alignment accuracy, within the design margin of ±2 µm. In the flip-chip bonding process, the chips and the substrate are briefly heated to above 300°C, leading to the alloying of the Au/Sn microbumps into the substrate's Au contacts. This forms an electrical and mechanical connection between the chip and the substrate. Small-signal RF measurements of back-to-back flip-chip transitions showed an insertion loss below 0.5 dB per interconnect, and a return loss of more than 10 dB from DC up to 250 GHz. So far, these are the best reported figures for flip-chip mounts in this frequency range.



06 *Stripline waveguide chip mounted onto AlN substrate with coplanar RF lines*

Research in Focus

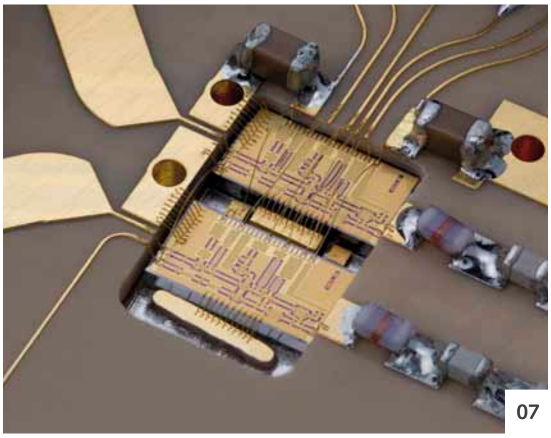
Digital power amplifier with improved efficiency

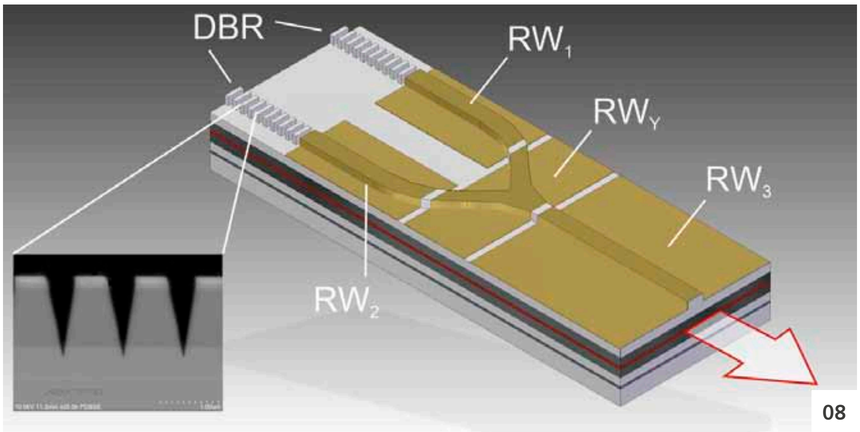
Digital power amplifier (PA) concepts are highly attractive for the future development of the wireless infrastructure. Today, the base stations‘ transmitter architecture is already almost fully digitized, except for the radio-frequency (RF) power amplifier. This is the reason why FBH has been working on digital PA modules for a number of years. Recently, in a joint experiment with the Japanese company NEC, the FBH successfully transferred the Doherty concept to the “digital world”. So far, it has only been applied for analog input signals. To achieve this, two PAs were operated in parallel – one of them is effectively only switched on at full-scale, which significantly enhances efficiency at power back-off. The FBH H-bridge PA module was driven by an envelope delta-sigma modulator from NEC. Compared to conventional balanced digital PAs the amplifier shows up to 20 % higher efficiency when driven between 6 dB and 12 dB below full-scale. For broadband communication signals with modern modulation schemes like WCDMA the improvement in efficiency is around 10 %. Current efforts are devoted to further enhancing PA efficiency for back-off operation beyond 10 dB.

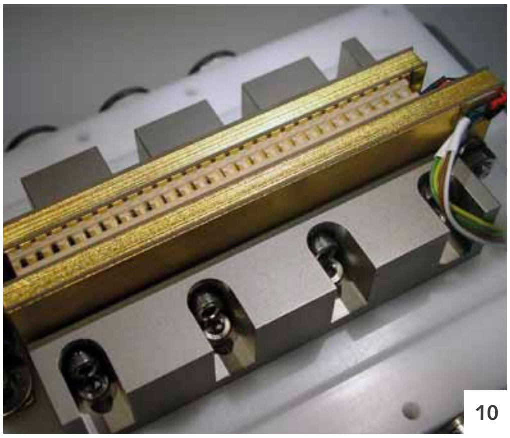
Dual-wavelength diode lasers – enabling miniaturized Raman sensor systems for real-world applications

The FBH develops dual-wavelength diode lasers meeting the respective demands of different spectroscopic applications including shifted excitation Raman difference spectroscopy (SERDS). SERDS allows to distinguish clearly between Raman and disturbing background signals like fluorescence and ambient light, effectively paving Raman spectroscopy its way out of the lab into real-world applications. Their small size and low power consumption enables to integrate these devices into miniaturized systems for in-situ measurements in security, food control, and point-of-care diagnostic areas.

These diode lasers are developed within the BMBF-funded project DiLaRa reaching output powers up to 100 mW and are available at 785 nm and 671 nm wavelengths. Moreover, they deliver grating-stabilized laser light, enabling to switch between the two necessary excitation wavelengths for SERDS by current. The applicability of these light sources for in-situ Raman measurements is currently investigated in precision agriculture within the EU-funded project USER-PA. Here, Raman spectroscopy is utilized to yield information on growth, irrigation, and fertilization status of fruits.







07 *Chips (detail) of class-D power amplifier module for mobile communication base stations*
08 *Dual-wavelength diode laser – basis for portable real-world Raman sensor systems*
09 *FBH's LED module irradiating broccoli sprouts with UV-B light at 310 nm wavelength*
10 *Stack consisting of 28 laser diodes – two stacks form one pump module delivering 6 J pump energy with 200 Hz repetition rate*

UV irradiation – to boost health-promoting compounds in plants

Epidemiological studies revealed that a high consumption of fruits, vegetables, and herbs comes along with a lower risk for both cancer and cardiovascular diseases. This protective effect is mostly due to secondary metabolites to be found in plant tissues. Recently, it has been shown that low dosage exposure to UV-B radiation may positively influence the biosynthesis of these organic compounds during plant growth. The issue is examined jointly by FBH and Leibniz Institute of Vegetable and Ornamental Crops (IGZ). Up to now, conventional low-pressure mercury gas-discharge fluorescent lamps have been used as UV-B radiation sources. These lamps deliver only a broadband UV-B radiation making it impossible to determine the wavelength-dependent action spectra of secondary plant metabolites. However, UV-B LEDs recently developed at FBH feature a narrow emission spectrum (half width < 10 nm) and a peak emission wavelength that can be tailored to ideally trigger specifically health-promoting secondary plant metabolites.

First experiments have been accomplished with an UV-B LED-based module with an emission at 310 nm. An adjustable uniform irradiance of up to 0.1 W m^{-2} was obtained at a working distance of 30 cm. That way, the formation of secondary metabolites in Arabidopsis leaves and broccoli sprouts could be successfully enhanced. The research activities will now be intensified within the Advanced UV for Life consortium, funded in the context of the BMBF competition Zwanzig20.

Product in Focus

High-power diode laser modules for short-pulse lasers in high energy class applications

Short-pulse lasers delivering a high output power along with a high repetition rate are highly requested in novel applications such as X-ray generation, and for studies into laser-induced fusion systems for future energy production. Up to now, the key figures of short-pulse lasers, high power and high repetition rate, are usually limited to either one of these features. Now, such a powerful light source offering both characteristics has been developed within a joint project by the FBH and the Max Born Institute (MBI). The MBI is responsible for the overall system, an optically pumped solid-state disk laser, whereas the FBH develops the required pump modules. Each module consists of 56 laser diodes closely arranged together which deliver an overall pump energy of 6 J with a 200 Hz repetition rate. To couple the single laser beams into a glass fiber with highest efficiency, a relatively simple setup could be used due to FBH-made customized chips and a newly developed mounting technology which allows a laterally coupled heatsink. The power conversion efficiency at working point is over 60 % and a coupling efficiency of more than 90 % was achieved.

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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Imprint

Publisher:
Ferdinand-Braun-Institut,
Leibniz-Institut fuer
Hoechstfrequenztechnik
Gustav-Kirchhoff-Str. 4
12489 Berlin, Germany
Phone +49.30.6392-2626

Editors: Petra Immerz, Gisela Gurr

Layout: telegrafik berlin

Images: (top down)
title illustration: iStock, background: B. Schurian; B. Schurian: p. 3 (middle), p. 4 (03), p. 7 (07) M. Schönenberger: p. 3 (portrait) IGZ: p. 7 (09) further images/graphics by FBH, icons p. 2: Freepik from flaticon.com (CC BY 3.0)