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Heterointegration – combining the best of two technology worlds

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- Electronics – joining InP with Si-BiCMOS and CMOS
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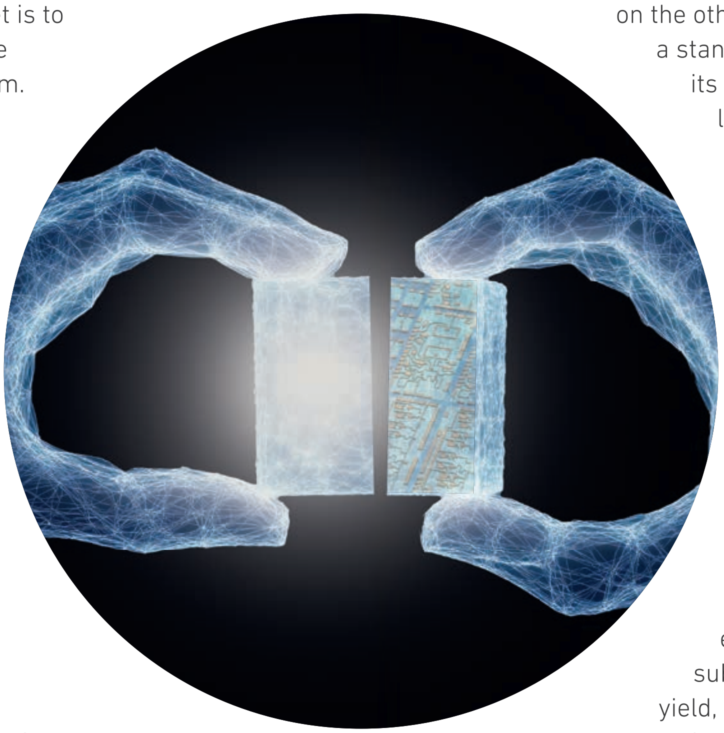
Heterointegration – combining the best of two technology worlds

The concept heterointegration has been around in the microelectronic community for decades. It describes approaches to combine different semiconductor technologies to leverage the specific strengths of each. The target is to push the performance of the final heterointegrated system. As a typical example, CMOS is joined with the III-V materials GaN or InP to boost output power at microwave and mm-wave frequencies.



While the objective of heterointegration is well-defined, the term itself is used quite generically. It covers a wide spectrum of integration techniques. At one end, purely monolithic approaches combine different materials within the same process. At the other, system-in-package (SiP) solutions join chips from different material platforms in a common module or share the same interposer. One should note, that the integration technique also determines the partioning levels which are possible – especially at high frequencies. A monolithic solution, for example, can merge different transistor technologies within the same subcircuit. In contrast, in-package approaches introduce interconnect parasitics that hinder this capability, confining SiP concepts to the subcircuit or circuit level.

The promise of overcoming limitations of Si-based electronics and photonics processes has made heterointegration highly attractive. Clearly, monolithic heterointegration poses the toughest challenge, but it also offers the greatest potential. It enables the highest level of flexibility and supports volume scaling, but has yet to demonstrate feasibility in a commercial scenario. The in-package version, on the other hand, may not really differ from a standard hybrid package. As a result, its performance gains often remain limited and interconnect parasitics render the SiP solution impractical in the mm-wave or sub-mm-wave range.

> *The promise of overcoming limitations of Si-based electronics and photonics processes has made heterointegration highly attractive.*

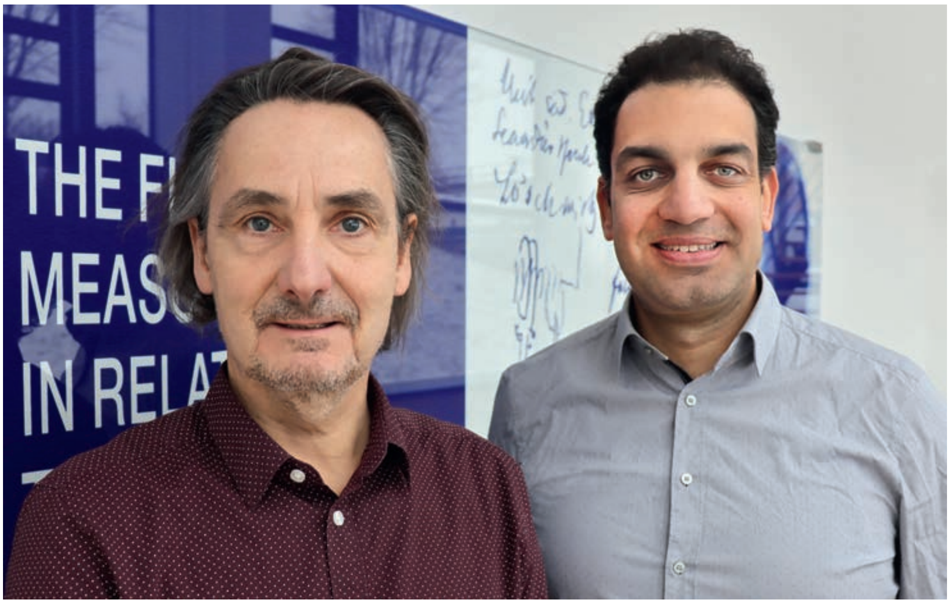
Chiplets – the next step in heterointegration

In view of this dilemma, the chiplet approach has become a hot topic in the heterointegration field. It was pioneered as a technology shift that partitions one huge, complex chip comprising an entire system into smaller chiplets, each dedicated to a specific subfunction. This strategy improves yield, though at the cost of additional mounting efforts. Today, it has become mainstream in several CMOS digital technologies. Even when all chiplets are CMOS-based, the approach still adds value because it allows to combine different nodes to optimize performance versus cost.

The chiplet approach can also be tailored to realize heterointegration of III-V processes with silicon in electronics and photonics. The advantage is in avoiding major modifications to the basic semiconductor processes. Technology mixing and the associated cleanroom compatibility issues occur only at the final step, when the various chiplets are combined to form the heterointegrated chip. The challenge is to develop a mounting approach that avoids chiplet degradation due to the combination of the different material systems and, at the same time, ensures seamless electrical, RF, optical, and thermal connectivity.

Heterointegration @ FBH

At FBH, we work on heterointegration solutions in both electronics and photonics within the European pilot line APECS. In electronics, we integrate bipolar InP chiplets for mm-wave and sub-mm-wave frequencies with SiGe-BiCMOS and CMOS platforms. In photonics, we combine GaAs laser diode chiplets with SiN-based optical interposers to build photonic integrated circuits (PICs).



Dr. Sven Einfeldt (left), Dr. Hady Yacoub (right)

Interested?

Then please get
in touch with us!

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Benefits of a cooperation with FBH

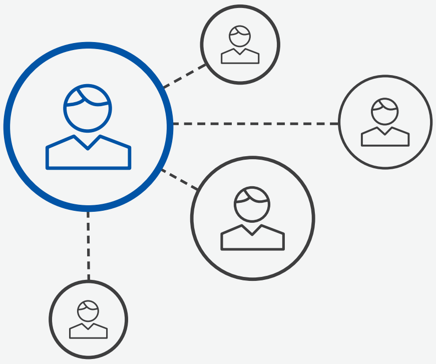
- **Internationally recognized** R&D – diode lasers as well as RF and quantum devices
- **Highly-skilled** scientific team in chip and circuit design, epitaxy, wafer processing, and device characterization
- **Bridging the gap** between basic and application-oriented R&D due to close cooperation with universities and industry
- **Full process chain** available in-house – from chiplets to modules and systems
- **Processing capabilities** able to handle arsenides, phosphides, and nitrides – with wafers sizes up to 200 mm
- **Developing supply chains** with German and European technology partners, supported by state-of-the-art 2,000 m² cleanroom facilities

Heterointegration processes include

- **Laser chiplets** covering a broad wavelength range from the visible to the near infrared
- **InP-DHBT** multi-project wafer process for mm-wave ICs with design support and PDK

Services offered by FBH

- Joint research projects
- Industrial contracts
- Small-scale series
- Prototypes
- Consulting
- Technology services
- Technology transfer

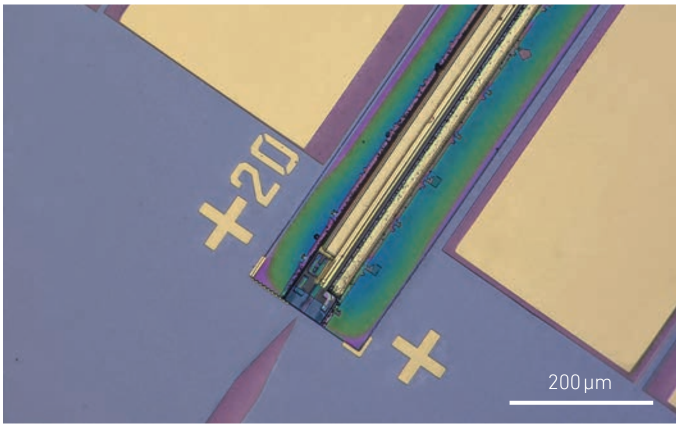


How to work with us

The FBH is one of the technology partners contributing III-V heterointegration processes in both photonics and electronics to the European APECS pilot line. APECS offers heterointegrated solutions from a single source across different institutions. **www.apecs.eu**

APECS

Photonic heterointegration – from space-based metrology to a pocked-size optics lab



Laser chiplet printed in the recess of a SiN platform. The light is coupled into a tapered waveguide, metal pads are used for later contact with the chiplet.

FBH builds on extensive expertise in diode lasers, primarily based on GaAs and increasingly also on GaN. These devices cover emission wavelengths from near-infrared to ultra-violet. Complex optical and electro-optical systems containing such lasers will only find their way into mass markets if they can be manufactured as micro-integrated, low-cost solutions. Today, hybrid integration of diode lasers in photonic integrated circuits (PICs) typically relies on edge coupling of components via classic assembly and interconnect methods, or on flip-chip mounting. These approaches enable application-relevant output powers of around 10 mW and intrinsic linewidths down to a few hertz. However, the level of integration is limited and manufacturing is difficult to scale.

Photonic integration at FBH

We have developed a monolithic GaAs-based integration platform. The PIC chip combines one or more gain sections with passive waveguide sections and wavelength-selective elements. To fabricate these structures, we use a mature in-house process that relies on two epitaxy steps. Between these steps, we selectively remove the active region from the wafer. At 1064 nm, the approach delivers, for example, passive ring resonators with Q-factors of a quarter million and PICs with output powers of over 40 mW. The platform can also be extended to shorter wavelengths down to 950 nm without compromising lifetime or laser power. Increasingly, we focus on technologies for heterogeneous integration. The approach is well established in optical data and telecommunications, where InP-based diode lasers are used that emit around 1.3 µm and 1.5 µm, respectively. For GaAs-based lasers, however, heterogeneous integration is far less mature – and even less developed for combining various chiplets with different wavelengths on the same platform.

We use SiN as the PIC platform because it offers low optical losses, enables narrow linewidths, is CMOS-compatible, and commercially available. The GaAs laser chiplets are transferred to this platform using micro-transfer printing (see info box). We have already successfully developed transferable laser chiplets at wavelengths of 638 nm and 890 nm, as well as for the range between 900 nm and 1000 nm. Together with partners, we have demonstrated their functionality in a SiN PIC environment using evanescent coupling. Chiplets with plasma-etched facets also show strong potential. They enable optical butt coupling to the PIC and thus wavelength-independent integration concepts.

Next steps toward scalable quantum photonics

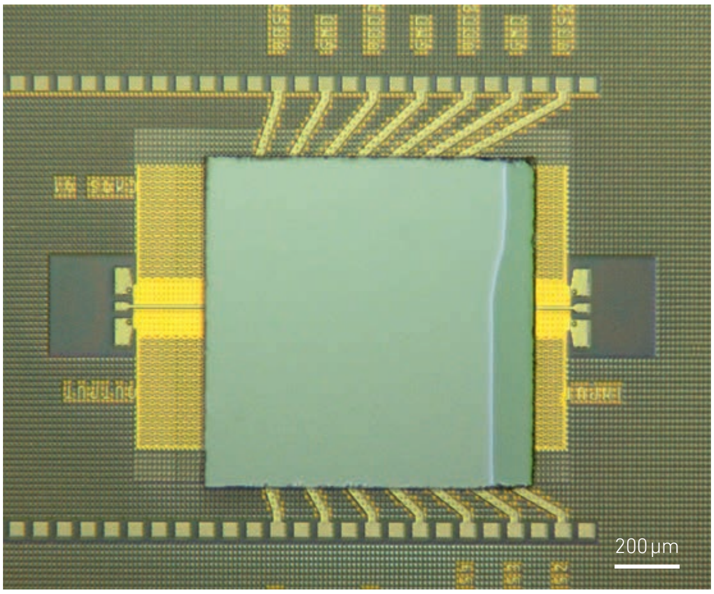
Quantum technologies are advancing rapidly. Ultra-high-precision optical clocks and high-speed quantum computers are among the developments that will revolutionize everyday life. These systems depend on integrated laser sources emitting at a wide range of wavelengths, often with intrinsic linewidths below 1 kHz. We are developing such sources using various laser resonators formed by a SiN PIC, into which several GaAs laser chiplets are heterogeneously integrated. The available on-chip laser power will scale to 10 – 100 mW and we will establish generic and scalable manufacturing processes.

Micro-transfer printing at a glance

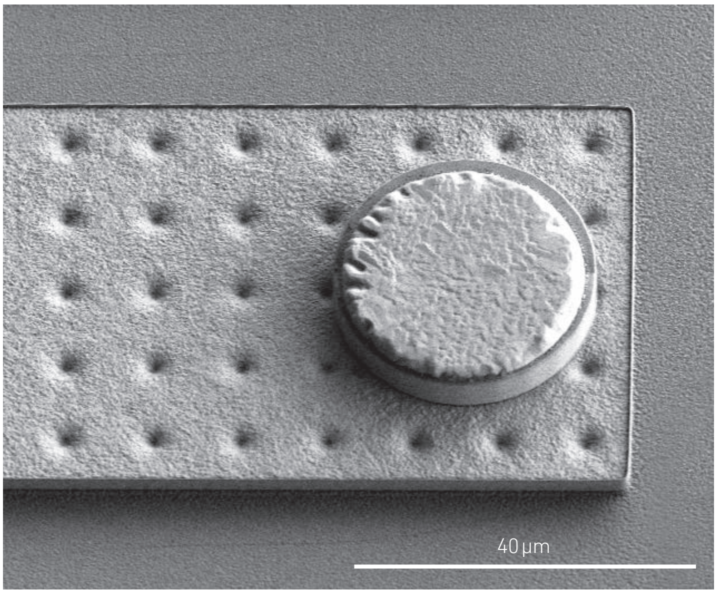
FBH fabricates laser chiplets by growing the functional semiconductor layers epitaxially on top of a sacrificial layer. During wafer processing, wet-chemical etching selectively removes this sacrificial layer. The result is a free-standing laser chiplet, only a few micrometers thick, which remains attached to the wafer solely by special anchor structures (tethers). A polymer stamp then picks the chiplet from the source wafer and places it onto a target wafer with PICs. An optional adhesive agent fixes the chiplet in position. The optical connection between the chiplet and its surroundings is achieved using a polymer. Further integration steps, including encapsulation and electrical contacting, are performed. This micro-transfer printing (available from X-Celeprint) process enables the microintegration of components of various designs and materials on a common PIC platform.

X-Celeprint micro-transfer printer in use at FBH.

Electronics heterointegration: joining indium phosphide with Si-BiCMOS and CMOS



Heterointegration of a III-V chip with silicon CMOS.



SEM image of a micro-bump used for RF heterointegration.

Recent advances in microelectronics have brought heterointegration into sharp focus. Complex systems have been previously realized in two distinct approaches. Either component-based integration through well-defined packaging interfaces or high-scale monolithic integration within a single material system. Both strategies, however, have clear drawbacks. Component-based approaches constrain form factor. Monolithic integration restricts material flexibility.

Heterointegration addresses these limitations, offering an intermediate integration platform that combines these technologies without inheriting their drawbacks. In other words, it delivers the best of both worlds. At FBH we also pursue this approach to enable new system design concepts, which can harness the strengths of each semiconductor technology while preserving overall system performance. One of the main advantages of heterointegration is evident in wireless communications.

In wireless transmitters, the output power directly limits range and data rate. More precisely, the emitted isotropic radiated power (EIRP) defines the achievable range of the communications link. This constraint becomes particularly critical for sub-THz systems, where the available output power remains a scarce resource. Increasing EIRP by using active antenna arrays, however, is in this frequency range only feasible to a limited extent, since the energy consumption of the RF part quickly rises to prohibitively high values.

As a result, each transmitter, i.e., each power amplifier (PA), requires both high output power and high power-added efficiency. Unfortunately, these two quantities decrease severely with increasing frequency. In the sub-THz range, RF-CMOS offers only very limited performance. SiGe-BiCMOS shows improvements, but still falls short of the requirements. Only III-V components, primarily InP, provide a decisive gain. At 150 GHz, InP power amplifiers achieve about ten times higher output power at twice the efficiency of SiGe solutions.

This advantage alone does not solve the system challenge. Designers should implement only some critical functions in InP. For the remaining transceiver, (Bi)CMOS clearly remains the technology of choice. High operating frequencies further complicate integration and interconnect design. These constraints call for a dedicated heterointegration approach, which allows to combine InP chiplets for critical front-end functions, such as PA and switch, with a CMOS system-on-chip in a scalable way.

FBH heterointegration in electronics

We have developed a novel heterointegration strategy for microelectronics. A micro-bump-based approach lays the foundation for chiplet heterointegration at FBH. By exploiting the high lithography resolution of backend of line (BEOL) processes, we fabricate micro-bumps as small as 20 µm directly on top of the chiplets' routing layers. Unlike conventional stud bumps, micro-bumps offer closer proximity to the integration platform. This vicinity reduces RF interconnect losses at high frequencies to less than 1 dB at 300 GHz and significantly broadens the range of applications.

FBH achievements in heterointegration

Heterogeneous integration drives greener cloud and edge computing hardware

HiCONNECTs brings together 64 partners from 15 countries to develop next-generation cloud and edge computing platforms that are sustainable, energy-efficient, and bring cloud services closer to end users. The EU-funded projects' focus is on heterogeneous integration of integrated circuits, discrete and photonics technologies into a system in a package that improves technological reliability and efficiency.

Since 2022, FBH has contributed to several technical work packages. We have made substantial progress on heterogeneous integration of high-speed InP electronics with photonic components for systems operating beyond 100 GHz. We designed and fabricated high-speed electronic building blocks, including drivers, traveling-wave amplifiers, transimpedance amplifiers, multiplexers, and demultiplexers. The devices achieve bandwidths well above 100 GHz. See figure 1.

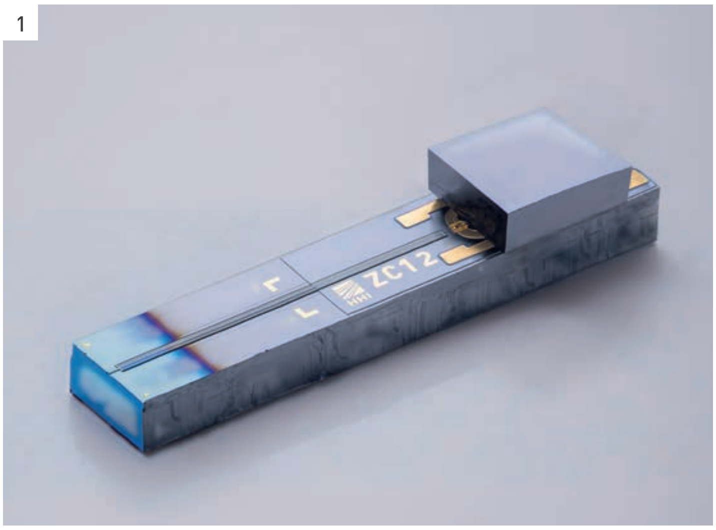
Advancing 6G hardware: heterointegration boosts performance at 150 GHz bands

The FBH has also contributed to technical work packages within the 6G Research and Innovation Cluster (6G-RIC), a research hub designed to lay the scientific and technical foundations for the upcoming 6G network infrastructures. The BMFTR-funded interdisciplinary collaboration of 32 research groups was focused on researching and developing a secure, flexible and open communications infrastructure as the basis for successful digitization in business and all areas of society. With this goal in mind, we have developed high-frequency electronics using FBH's in-house InP-MMIC process to realize high performance in the D-band frequency range (140...170 GHz). To achieve this, we have adopted the heterointegration technology approach to realize complex high-frequency systems with both SiGe-BiCMOS and CMOS. Our team has shown functional heterointegration interfaces for both InP-on-BiCMOS and InP-with-CMOS for frequencies up to 300 GHz, with functional circuits demonstrated up to 140 GHz. Combining InP-based transmitter stages with BiCMOS transceivers boosts output power and thus system performance, primarily extending maximum range of wireless links at those frequencies.
See figure 2.

Transfer-printable GaAs gain chiplets for application-specific PICs

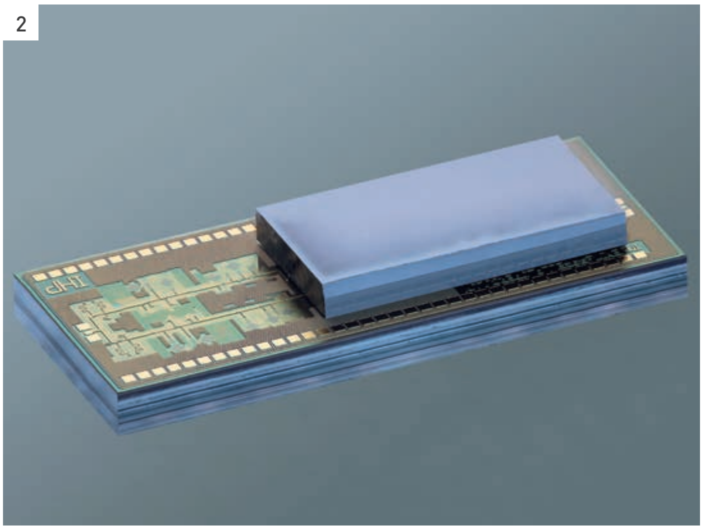
FBH has developed thin (2 – 4 µm) transfer-printable GaAs gain chiplets. The process uses selective underetching of the active device which remains attached to the substrate by small tethers. Within the European joint project VISSION, our partner imec transfer-printed these chiplets onto a SiN waveguide. Evanescent coupling between gain chiplet and waveguide forms a laser that delivers more than 1 mW output power at a wavelength of around 960 nm. The same technology also supports butt coupling of devices by printing into a recess on the waveguide. In this way, lasers can be manufactured for the entire NIR wavelength range down to red wavelengths. We will use this technology to realize application-specific PICs. See figure 3.

1



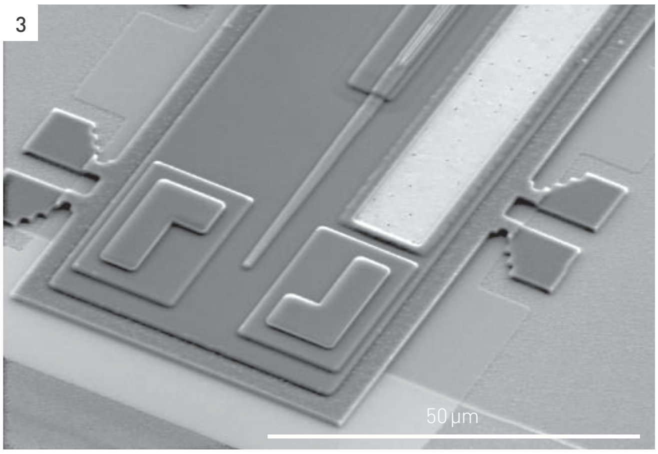
Heterointegrated InP-based transimpedance amplifier (TIA) on a photo diode receiver using FBH's heterointegration process. The complete system offers broadband operation from DC up to 80 GHz.

2



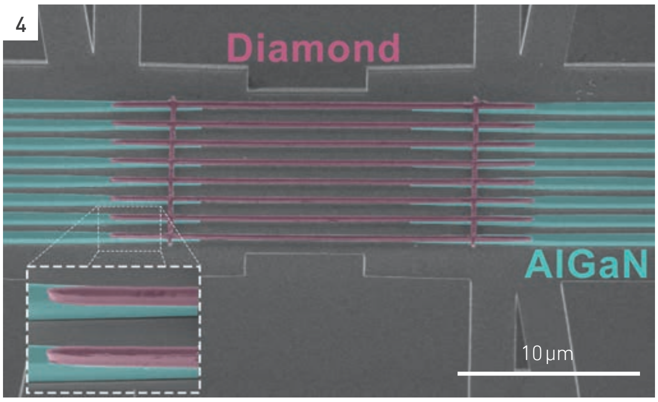
Heterointegrated InP power amplifier and switch on SiGe-BiCMOS transceiver.

3



GaAs gain chiplet hanging freely on anchors prior to microtransfer printing.

4



Photonic chip-integrated (green) diamond nanophotonic quantum devices (red).

Heterointegration of diamond nanostructures into AlGaN/AlN-based PICs

Photonic integrated circuits (PICs) combined with efficient spin-photon interfaces offer a promising route toward scalable quantum processors and quantum networks. At FBH, we are developing a hybrid platform that integrates diamond quantum photonic devices with AlGaN/AlN PICs.

Diamond color centers rank among the most promising spin-photon interfaces, providing optically addressable spin states with long coherence times. Photonic nanostructures can further enhance their coherent photon emission. At FBH, we already realized this concept with photonic crystal cavities, including the sawfish design.

Meanwhile, AlGaN/AlN PICs provide a broad transparency window, strong nonlinear electro-optical properties, and compatibility with wafer-scale processing. These features enable low-loss, reconfigurable photonic circuits. By heterogeneously integrating diamond devices onto AlGaN/AlN waveguides – and using designs that reach ~97 % coupling efficiency in simulations – we aim to realize a fully integrated quantum photonic platform. See figure 4.

APECS – your access to cutting-edge technologies

The pilot line for "Advanced Packaging and Heterogeneous Integration for Electronic Components and Systems" provides major industrial companies, SMEs, and start-ups with low-threshold access to cutting-edge technologies and ensures secure semiconductor value chains. APECS focuses on the scalable industrial transfer of newly developed innovations in the field of heterointegration, thus facilitating the transition from lab demonstrations to industrial manufacturing.

We are one of the institutes working closely with European partners to set up the APECS pilot line. This line will strengthen Europe's technological resilience and boost global competitiveness in the semiconductor industry.

FBH's technological portfolio within APECS

Bipolar InP chiplets

- for high-frequency applications in the W and D bands. We combine our InP chiplets with SiGe-BiCMOS chips from the Leibniz institute IHP, thus creating heterointegrated high-performance transceivers.
- for broadband circuits, e.g., drivers in electro-optical transmitters, which are used along with photonic InP components from Fraunhofer HHI.

GaAs laser diode chiplets

- for the integration on optical interposers (SiN), to form photonic integrated circuits (PICs) operating at a wide range of wavelengths (620...1180 nm).

APECS goes beyond conventional system-in-package methods and aims to deliver robust and trustworthy heterogeneous systems that significantly increase the innovative capacity of the European semiconductor industry.

The Ferdinand-Braun-Institut (FBH) is an application-oriented research institute in the fields of high-frequency electronics, photonics, and quantum technologies. It researches electronic and optical components, modules, and systems based on compound semiconductors.

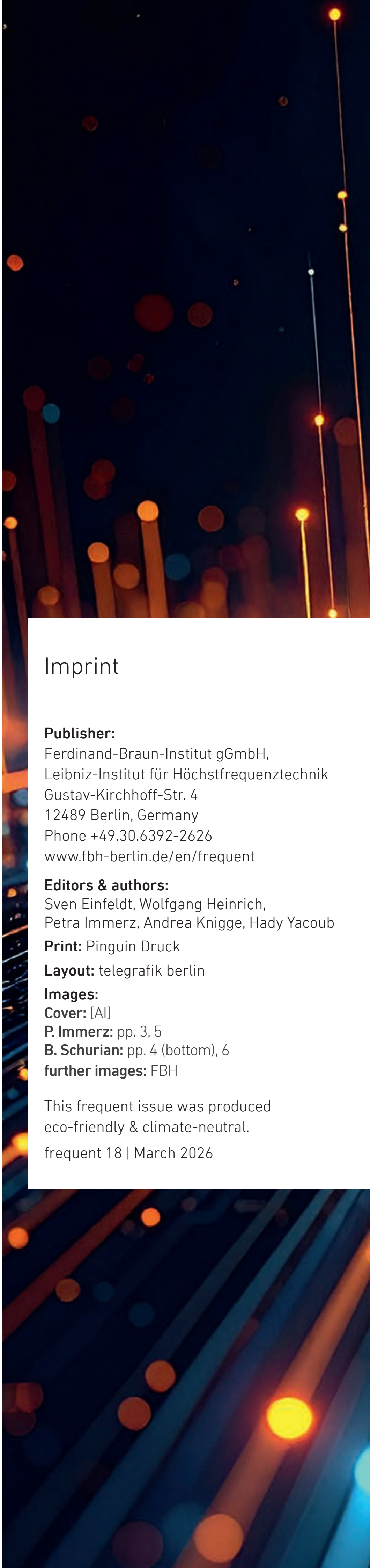
In photonics, FBH develops light sources from the near-infrared to the ultraviolet spectral range: high-power diode lasers with excellent beam quality, UV light sources, and hybrid laser modules. Applications range from materials processing, medical technology, and high-precision metrology to optical communication in space.

In quantum technologies, FBH translates laboratory-scale proof-of-concept experiments into robust, application-ready systems. Developments include quantum photonic components, hybrid micro-integrated modules, compact quantum sensors, diamond nanophotonic devices, and photonic quantum chips for secure communication, high-precision measurements, sensors, and computing platforms.

In high-frequency electronics, FBH develops high-efficiency multi-functional microwave power amplifiers and millimeter-wave transceivers targeting energy-efficient wireless communications, industrial sensing, and imaging. In addition, the institute specializes in broadband drivers and transimpedance amplifiers for optoelectronic transceivers as well as high-speed drivers for high-power diode lasers.

The FBH is a center of competence for III-V compound semiconductors covering the full range of capabilities, from design through fabrication to device characterization. Within Research Fab Microelectronics Germany (FMD), FBH has joined forces with 14 other German research institutes, thus offering the complete micro and nanoelectronics value chain as a one-stop shop.

In close cooperation with industry, FBH turns excellent research results into market-oriented products, processes, and services – additionally transferring innovative product ideas into spin-off companies. The institute thereby offers its customers complete solutions and know-how – from design to ready-to-use modules and prototypes.



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