Annual Report
Jahresbericht
2013

Leibniz
Ferdinand-Braun-Institut

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Technical solutions for the needs of modern societies are becoming increasingly capable. However, performance demands continue to rise. This applies for communications, health, and energy as much as for cross-sectional technologies like industrial production engineering and aerospace technology. Research and development are essential to advance these technical solutions, up to completely new developments. The Ferdinand-Braun-Institut contributes with its top-level results in the research areas of microwave technology and optoelectronics. In 2013, FBH scientists succeeded, among others, in developing optically pumped UV laser diodes with the shortest emission wavelength ever demonstrated for a semiconductor laser. In the field of microwave technology, energy-efficient power amplifiers have been developed that process all signals digitally up to the final stage. This way, they enable wireless infrastructure to cope with future technical requirements and make an important contribution towards "Green IT". With CryoLaser, the FBH generated a great deal of international attention. This project aims to develop particularly efficient laser diodes for next-generation particle accelerators, with the optical power density to be increased by a factor of 10 and the conversion efficiency to over 80 percent.

These are only some examples for the considerable number of research and industrial projects the FBH is involved in, from cooperation in Asia to industrial partnerships in the USA to an abundance of European and national research projects. The Ferdinand-Braun-Institut additionally succeeded in further expanding its university collaborations and Joint Labs with universities from Berlin, Cottbus, and Frankfurt/Main. The UV lasers mentioned above are one result of the cooperation within the Joint Lab GaN Optoelectronics with TU Berlin. Increasingly, the institute assumes responsibility as the coordinator in its projects, as with "Advanced UV for Life" which has prevailed in the "Zwanzig20 – Partnership for Innovation" competition of the Federal Ministry of Education and Research (BMBF). The consortium led by the FBH focuses on novel UV semiconductors with tailor-made properties and applications. Until 2020, it is supported with up to 45 million Euros. These funds are used for comprehensive R&D activities, for example to activate molecular switches in vegetable cells by irradiation with UV light. Thus, "Advanced UV for Life" is currently the largest of the more than 170 current projects handled by the FBH in 2013.

The growing number of national and international projects emphasizes the impressive development that the Ferdinand-Braun-Institut has taken in the last decade. Accordingly, the number of FBH's employees has nearly doubled in the last ten years, and the institute therefore also spatially reaches its limits. In 2013, the foundation stone was laid for a 1,800 square-meter expansion building with additional laboratory and office space to remedy the situation.

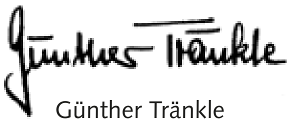
In line with its research assignment, the FBH is ensuring the quick and sustainable transfer of results to the industry. These activities comprise multifaceted and long-term collaborations with companies as well as the current formation of spin-offs, with three new companies adding only in 2013. The FBH continuously and intensely cooperates with more than 50 enterprises. Many of the electronic and optoelectronic components and modules arising from these connections are world-wide unique. This makes the FBH a core part of the value chain for many of these industrial partners. A special focus in this context is on companies from the region, where the institute significantly contributes to their market success.

Due to the support of our funding authorities, excellent technical equipment for research and development is available at the institute. In 2013, among others, a wafer stepper was brought into service. This large equipment is a crucial tool at FBH, enabling photolithographic structuring of semiconductor devices down to the sub-micrometer range. We therefore thank our funding federal and state authorities as well as the European Union for providing us with the basis for research at the highest level.

We realize our results jointly with our partners and customers, whom I like to express my appreciation for the confident and long-term cooperation. Many valuable stimuli come from their side, helping us to transfer our research into industrial-suited applications. However, all of this would not be possible without our dedicated employees with their expert knowledge, thus achieving internationally recognized results.

I am looking forward to the further prosperous cooperation with all of you and wish you an inspiring reading of 2013's developments and events.

Yours sincerely,



Günther Tränkle

Technische Lösungen für den Bedarf moderner Gesellschaften werden immer leistungsfähiger – die Anforderungen steigen jedoch weiter. Das gilt in der Kommunikation, Gesundheit und Energie ebenso wie für Querschnittstechnologien wie die industrielle Produktionstechnik oder die Raumfahrt. Forschung und Entwicklung sind unverzichtbar, um diese technischen Lösungen voranzubringen bis hin zu vollständig neuen Entwicklungen. Das Ferdinand-Braun-Institut trägt dazu mit seinen Spitzenergebnissen in den Forschungsbereichen der Mikrowellentechnik und Optoelektronik bei. Unter anderem gelang FBH-Wissenschaftlern 2013 die Entwicklung von optisch gepumpten UV-Laserdioden mit der kürzesten Emissionswellenlänge, die bisher für Halbleiterlaser demonstriert wurde. Im Bereich der Mikrowellentechnik wurden neuartige Leistungsverstärker entwickelt, die die Signale bis zur Endstufe digital verarbeiten. Damit machen sie die drahtlose Infrastruktur für künftige Anforderungen tauglich und leisten einen wichtigen Beitrag in Richtung „Green IT". Große internationale Aufmerksamkeit erreichte das FBH mit seinem Projekt CryoLaser, in dem besonders effiziente Laserdioden für die nächste Generation von Teilchenbeschleunigern entwickelt werden. Die optische Leistungsdichte dieser Laser soll um den Faktor 10 und der Wirkungsgrad auf über 80 Prozent gesteigert werden.

Dies sind nur einige Beispiele für die zahlreichen Forschungs- und Industrievorhaben, in die das FBH eingebunden ist: von Kooperationen in Asien über Industriepartnerschaften in den USA bis hin zu einer Fülle von europäischen und nationalen Forschungsprojekten. Seine Hochschulkooperationen und Joint Labs mit Universitäten aus Berlin, Cottbus und Frankfurt/Main hat das Ferdinand-Braun-Institut 2013 weiter ausgebaut. Die erwähnten UV-Laser sind im Joint Lab GaN-Optoelektronik mit der TU Berlin entstanden. Immer häufiger übernimmt das Institut in seinen Projekten als Koordinator Verantwortung. So auch bei „Advanced UV for Life", das sich im Wettbewerb „Zwanzig20 – Partnerschaft für Innovation" des Bundesministeriums für Bildung und Forschung (BMBF) durchsetzen konnte. Das vom FBH geleitete Konsortium zielt auf neuartige Halbleiter-UV-Bauelemente mit maßgeschneiderten Eigenschaften und Applikationen. Bis 2020 wird es mit bis zu 45 Millionen Euro gefördert – Mittel, die in umfassende F&E-Aktivitäten fließen werden, etwa zu molekularen Schaltern in Gemüsezellen, die mittels UV-Licht aktiviert werden. Damit ist „Advanced UV for Life" das zurzeit größte der mehr als 170 laufenden Vorhaben, die das FBH im Jahr 2013 bearbeitete.

Die wachsende Anzahl von nationalen wie internationalen Projekten unterstreicht die eindrucksvolle Entwicklung, die das Ferdinand-Braun-Institut im letzten Jahrzehnt genommen hat. So hat sich die Mitarbeiterzahl des FBH in den letzten zehn Jahren beinahe verdoppelt. Damit stößt das Institut auch räumlich an seine Grenzen – ein 1.800 Quadratmeter großer Erweiterungsbau mit zusätzlichen Labor- und Büroräumen, für den 2013 der Grundstein gelegt wurde, soll Abhilfe schaffen.

Entsprechend seinem Forschungsauftrag sorgt das FBH zugleich für den raschen und nachhaltigen Transfer in die Industrie. Diese Aktivitäten umfassen vielfältige und langjährige Kooperationen mit Firmen ebenso wie aktuelle Ausgründungen – gleich drei neue

Spin-offs kamen 2013 hinzu. Das FBH kooperiert kontinuierlich und intensiv mit über 50 Industrieunternehmen. Viele der in diesem Rahmen entwickelten elektronischen und optoelektronischen Komponenten und Module sind weltweit einzigartig. Das macht das FBH zu einem zentralen Bestandteil in der Wertschöpfungskette vieler dieser Unternehmen. Ein besonderer Fokus liegt dabei auf der Zusammenarbeit mit Unternehmen aus der Region, zu deren Markterfolg das FBH wesentlich beiträgt.

Dank der Unterstützung unserer Zuwendungsgeber steht dem FBH eine ausgezeichnete technische Ausstattung für Forschung und Entwicklung zur Verfügung. 2013 wurde unter anderem ein Waferstepper in Betrieb genommen, der fotolithografische Strukturierungen von Halbleiterbauelementen bis in den Submikrometerbereich ermöglicht – eines der zentralen Großgeräte am Institut. Unser Dank gilt daher den Geldgebern im Land Berlin, im Bund und in der Europäischen Union, die damit die Voraussetzungen für Forschung auf höchstem Niveau schaffen.

Unsere Ergebnisse realisieren wir gemeinsam mit unseren Partnern und Kunden, denen ich für die vertrauensvolle und langjährige Zusammenarbeit danke. Von ihnen kommen viele wertvolle Impulse, mit denen wir unsere Forschungen in industrietaugliche Applikationen überführen. All dies wäre jedoch ohne unsere engagierten Mitarbeiterinnen und Mitarbeiter, die mit ihrem Fachwissen international anerkannte Ergebnisse erzielen, nicht möglich.

Ich freue mich auf die weiterhin gute Zusammenarbeit mit Ihnen allen. Eine anregende Lektüre der Entwicklungen und Ereignisse aus dem Jahr 2013 wünscht Ihnen,

Ihr

Günther Tränkle

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FBH at a glance

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.

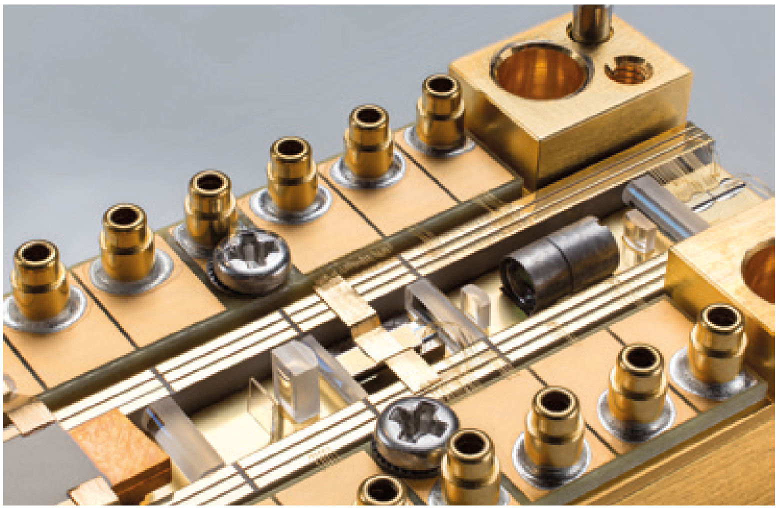
In close cooperation with industry, its research results lead to cutting-edge products. The institute also successfully turns innovative product ideas into spin-off companies. Thus, working in strategic partnerships with industry, FBH assures Germany's technological excellence in microwave and optoelectronic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

Das FBH im Profil

Das Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) erforscht elektronische und optische Komponenten, Module und Systeme auf der Basis von Verbindungshalbleitern. Diese sind Schlüsselbausteine für Innovationen in den gesellschaftlichen Bedarfsfeldern Kommunikation, Energie, Gesundheit und Mobilität. Leistungsstarke und hochbrillante Diodenlaser, UV-Leuchtdioden und hybride Lasersysteme entwickelt das Institut vom sichtbaren bis zum ultravioletten Spektralbereich. Die Anwendungsfelder reichen von der Medizintechnik, Präzisionsmesstechnik und Sensorik bis hin zur optischen Satellitenkommunikation. In der Mikrowellentechnik realisiert das FBH hocheffiziente, multifunktionale Verstärker und Schaltungen, unter anderem für energieeffiziente Mobilfunksysteme und Komponenten zur Erhöhung der Kfz-Fahrsicherheit. Kompakte atmosphärische Mikrowellenplasmaquellen mit Niederspannungsversorgung entwickelt es für medizinische Anwendungen, etwa zur Behandlung von Hauterkrankungen.

Das FBH ist ein international anerkanntes Zentrum für III/V-Verbindungshalbleiter mit allen Kompetenzen: vom Entwurf über die Fertigung bis hin zur Charakterisierung von Bauelementen.

Seine Forschungsergebnisse setzt das FBH in enger Zusammenarbeit mit der Industrie um und transferiert innovative Produktideen und Technologien erfolgreich durch Spin-offs. In strategischen Partnerschaften mit der Industrie sichert es in der Höchstfrequenztechnik die technologische Kompetenz Deutschlands.



Mission statement

... translating ideas into innovations

- We explore cutting-edge technologies for innovative applications in the fields of microwaves and optoelectronics. As a center of competence for III-V compound semiconductors, we are part of a worldwide network and achieve research results advancing the international state-of-the-art.

- We offer complete solutions as a one-stop agency – from design to ready-to-ship modules.

- In strategic partnerships with industry, we transfer our research results into cutting-edge products and thus ensure German technological leadership in microwaves and optoelectronics. By means of spin-off companies, we bring innovative product ideas into the market.

- We provide high-value products and services for our customers in the research community and industry which are tailored to fit their individual needs.

- We offer our employees an attractive and family-friendly working environment with interesting tasks and career prospects. To maintain top-level expertise we guide, assist, and encourage young scientists and train our staff.

- We specifically aim at increasing the proportion of female specialists and executive staff in the technical and scientific area and actively assist foreign colleagues with their integration.

Leitbild

... translating ideas into innovations

- *Wir erforschen Schlüsseltechnologien für innovative Anwendungen in der Mikrowellentechnik und Optoelektronik. Als Kompetenzzentrum für Verbindungshalbleiter arbeiten wir weltweit vernetzt und erzielen Forschungsergebnisse auf internationalem Spitzenniveau.*

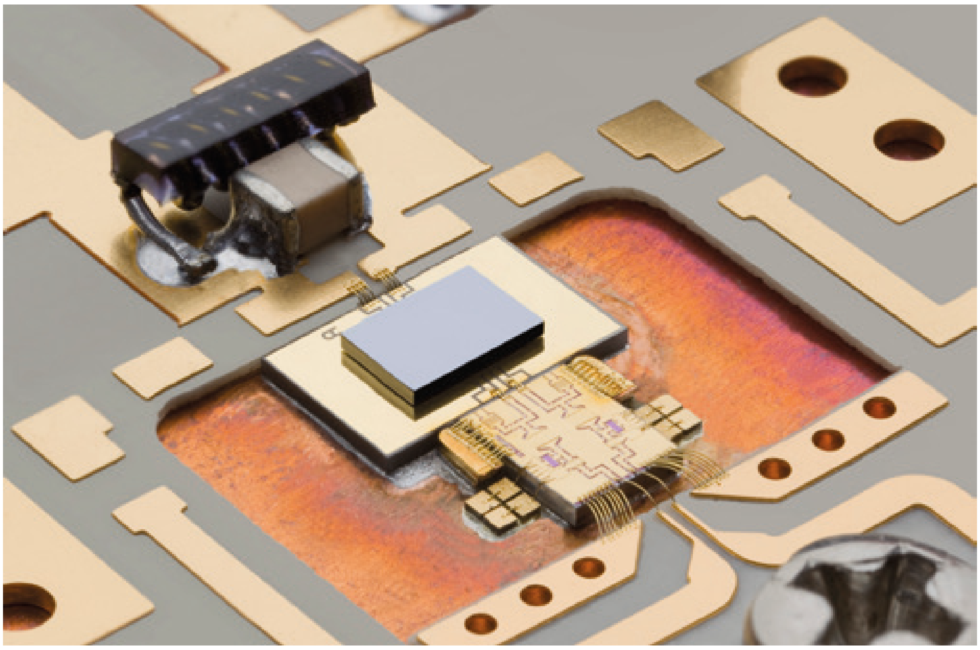
- *Wir bieten Lösungen aus einer Hand: vom Entwurf bis zum lieferfähigen Modul.*

- *Wir setzen unsere Forschung in strategischen Partnerschaften mit der Industrie in praktische Anwendungen um und sichern so die technologische Kompetenz Deutschlands in der Höchstfrequenztechnik. Innovative Produktideen transferieren wir erfolgreich durch Spin-offs.*

- *Wir offerieren hochwertige Produkte und Services, die exakt auf die Anforderungen unserer Kunden zugeschnitten sind.*

- *Wir bieten unseren Mitarbeitern ein stabiles, attraktives und familienfreundliches Arbeitsumfeld mit reizvollen Aufgabenstellungen und Entfaltungsmöglichkeiten. Unsere Zukunft sichern wir durch die gezielte Förderung des wissenschaftlichen Nachwuchses und die Ausbildung technischer Fachkräfte.*

- *Wir haben es uns zur Aufgabe gemacht, den Anteil weiblicher Fach- und Führungskräfte im technischen und naturwissenschaftlichen Bereich gezielt zu erhöhen sowie ausländische Kolleginnen und Kollegen aktiv bei der Integration zu unterstützen.*



Business areas & research

- **Microwave Components & Systems**
  - Front ends up to 100 GHz
  - Power amplifiers up to 10 GHz
  - Low-noise components
  - Microwave plasma sources
  - Terahertz electronics
  - Power modules
- **GaN Electronics**
  - Microwave transistors & MMICs
  - Power electronics
- **Diode Lasers**
  - Broad area lasers & bars (spectral range 0.6 - 1.2 µm)
  - High-brightness lasers (linewidth < 10 MHz)
  - Hybrid laser systems
  - Laser sensors
  - Laser metrology
- **GaN Optoelectronics**
  - UV LEDs
  - Nitride laser diodes
- **Materials & Process Technology**
  - GaN HVPE
  - Special optical devices
  - In-situ control techniques for MOVPE & HVPE
  - Laser micro processing
- **Science Management**
  - Technology transfer & marketing
  - Education & training management
  - Administration
  - IT support

Geschäftsbereiche & Forschung

- ***Mikrowellenkomponenten & -systeme***
  - *Frontends bis 100 GHz*
  - *Leistungsverstärker bis 10 GHz*
  - *Low-Noise-Komponenten*
  - *Mikrowellen-Plasmaquellen*
  - *Terahertz-Elektronik*
  - *Leistungsmodule*
- ***GaN-Elektronik***
  - *Mikrowellentransistoren & MMICs*
  - *Leistungselektronik*
- ***Diodenlaser***
  - *Breitstreifen & Barren (Spektralbereich 0,6 - 1,2 µm)*
  - *Hochbrillante Laser (Linienbreiten < 10 MHz)*
  - *Hybride Lasersysteme*
  - *Lasersensorik*
  - *Lasermetrologie*
- ***GaN-Optoelektronik***
  - *UV-LEDs*
  - *Nitrid-Laserdioden*
- ***Material- & Prozesstechnologie***
  - *GaN-HVPE*
  - *Optische Sonderbauelemente*
  - *In-situ Kontrolltechniken bei MOVPE & HVPE*
  - *Lasermikrostrukturierung*
- ***Wissenschaftsmanagement***
  - *Technologietransfer & Marketing*
  - *Bildungsmanagement*
  - *Verwaltung*
  - *EDV*

Competence & comprehensive services

The FBH 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.

- **Microwave Components & Systems**
  - Gallium nitride electronics: transistors & amplifiers (hybrid, MMIC) – design, production, small-scale series
  - Microwave plasmas
  - Electromagnetic simulation
  - Microwave measurement & device characterization

- **High-Power Diode Lasers & LEDs**
  - Gallium arsenide-based diode lasers with customized properties (output power, wavelength, spectral linewidth, brightness, efficiency) – design, production, small-scale series
  - Hybrid laser systems in the IR and visible spectral range
  - Gallium nitride lasers & UV LEDs
  - Reliability investigations

- **Processes & Materials**
  - Development and implementation of semiconductor processes (especially III-V semiconductors)
  - Epitaxial growth of customized III-V semiconductor layers
  - Optical components based on gallium arsenide (mirrors, semiconductor disks, SESAMs)
  - UV photodetectors

Lösungen & Services aus einer Hand

Für Partner aus Forschung und Industrie entwickelt das FBH hochwertige Produkte und Services, die exakt auf individuelle Anforderungen zugeschnitten sind. Seinem internationalen Kundenstamm bietet es Know-how und Komplettlösungen aus einer Hand: vom Entwurf bis zum lieferfähigen Modul.

- ***Mikrowellenkomponenten & -systeme***
  - *Galliumnitridelektronik: Transistoren & Verstärker (hybrid, MMIC) – Entwurf, Fertigung, Kleinserie*
  - *Mikrowellenplasmen*
  - *Elektromagnetische Simulation*
  - *Hochfrequenz- & Leistungsmesstechnik*

- ***Hochleistungsdiodenlaser & LEDs***
  - *Diodenlaser auf Galliumarsenid-Basis mit maßgeschneiderten Eigenschaften (Leistung, Wellenlänge, Linienbreite, Strahlgüte, Effizienz) – Entwurf, Fertigung, Kleinserie*
  - *Hybride Lasersysteme im IR- und sichtbaren Spektralbereich*
  - *Galliumnitrid-Laser & UV-LEDs*
  - *Zuverlässigkeitsuntersuchungen*

- ***Prozesse & Materialien***
  - *Entwicklung und Durchführung von Halbleiterprozessen (insbesondere III/V-Halbleiter)*
  - *Epitaxie kundenspezifischer III/V-Halbleiter-Schichtstrukturen*
  - *Optische Komponenten aus Galliumarsenid (Spiegel, Halbleiter-Scheiben, SESAMs)*
  - *UV-Fotodetektoren*

Contact
Kontakt

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Forschungsverbund Berlin e.V.

Forschungsverbund
Berlin e.V.

The Forschungsverbund Berlin e.V. comprises eight research institutes in Berlin – one of them being the Ferdinand-Braun-Institut. The institutes are active in the fields of natural sciences, life sciences, and environmental sciences. They pursue common interests within the framework of a single legal entity while preserving their scientific autonomy. As research institutes of national scientific importance, they are jointly funded by the German federal and state governments. The institutes share an administrative infrastructure (Common Administration, Head Dr. Manuela Urban) and belong to the Leibniz Association.

The institute directors and other senior scientists hold chairs at the Berlin/Brandenburg universities, thus ensuring close contact with teaching and research in higher education.

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Forschungsverbund Berlin e.V.

Der Forschungsverbund Berlin e.V., zu dem auch das Ferdinand-Braun-Institut gehört, ist Träger von acht natur-, lebens- und umweltwissenschaftlichen Forschungsinstituten in Berlin. Alle Institute sind wissenschaftlich eigenständig, nehmen aber im Rahmen einer einheitlichen Rechtspersönlichkeit gemeinsame Interessen wahr. Als Forschungseinrichtungen von überregionaler Bedeutung und gesamtstaatlichem wissenschaftspolitischen Interesse werden die Institute im Rahmen der gemeinsamen Forschungsförderung von Bund und Ländern finanziert. Sie verfügen über eine gemeinsame Verbundverwaltung (Geschäftsführerin Dr. Manuela Urban) und gehören zur Leibniz-Gemeinschaft.

Die Direktoren der Institute und weitere leitende Wissenschaftler haben Professuren an den Universitäten in Berlin/Brandenburg inne und sichern so die enge Verbindung zu Lehre und Forschung in den Hochschulen.

The institute in figures
Das Institut in Zahlen

Founded 1992
Gegründet 1992

	2012	2013
Staff / ***Team***	250	270
Scientists / *Wissenschaftlerinnen & Wissenschaftler*	82	85
PhD students / *Promovierende*	40	51
Student assistants & diploma students / *Studentische Hilfskräfte & Diplomierende*	25	28
Trainees / *Auszubildende*	10	11
Projects / ***Laufende Projekte***	162	171
Publications (peer reviewed) / ***Publikationen (referiert)***	61	103
Patents / ***Patente***	175	196
Talks (invited) / ***Vorträge (eingeladene)***	150 (23)	152 (33)

Budget (in million Euros)
Umsatz (Mio. Euro)

	2012	2013
Basic funding: State of Berlin and Federal Government / *Grundfinanzierung durch das Land Berlin und den Bund*	11,7	11,9
Public project funding / *Öffentliche Drittmittel*	8,2	8,3
Industrial contracts / *Industrielle Auftragsforschung*	1,8	1,9

Organizational chart
Organigramm

Board of Trustees of Forschungsverbund Berlin e.V.
Chairwoman Dr. J. Koch-Unterseher, SenWTF Berlin

Administrative Management
Dr. M. Urban
Managing Director of FV Berlin

Scientific Director
Prof. Dr. G. Tränkle
Director of the FBH

Science Management
N. Hübener, M.Sc.
Strategy / Technology / Transfer & Marketing / Education & Training / Administration / IT Support

Central Services
Communications / Quality Management / Technical Services

Business Areas

Microwave Components & Systems Prof.Dr.-Ing.W.Heinrich	GaN Electronics Dr.-Ing. J. Würfl	Diode Lasers Dr. G. Erbert	GaN Optoelectronics Prof. Dr. M. Kneissl
Power Amplifiers Low-Noise Components Terahertz Electronics Microwave Plasmas	Microwave Transistors & MMICs Power Electronics	BA Lasers & Bars High-Brightness Lasers Hybrid Laser Systems Laser Sensors Laser Metrology	Nitride Laser Diodes UV LEDs

Departments

Microwaves Prof.Dr.-Ing.W.Heinrich	Optoelectronics Dr. G. Erbert	Materials Technology PD Dr. M. Weyers	Process Technology Dr. O. Krüger
Electromagnetic Simulation Circuit Design Measurements & Packaging	Laser Design Laser Technology Mounting & Packaging Laser Measurements	Arsenides & Phosphides Nitrides Special Optical Devices Materials Analytics	Frontend Backend

University Cooperations
Prof. Dr.-Ing. G. Böck - Microwave Technology (TU Berlin) / Prof. Dr.-Ing. S. Dieckerhoff - Power Electronics (TU Berlin) /
Prof. Dr. M. Kneissl - Experimental Nanophysics and Photonics (TU Berlin) / Prof. Dr. V. Krozer - Terahertz Photonics (Uni Frankfurt) /
Prof. Dr. A. Peters - Optical Metrology (HU Berlin) / Prof. Dr.-Ing. M. Rudolph - RF and Microwave Techniques (BTU Cottbus Senftenberg)

Scientific advisory board
Wissenschaftlicher Beirat

Chair *Vorsitz*

Prof. Dr. Robert Weigel
Universität Erlangen-Nürnberg, Erlangen

Members *Mitglieder*

Dipl.-Ing. Bernd Adelseck
Cassidian Electronics, Ulm

Dr. Erich Auer
Tesat-Spacecom GmbH & Co. KG, Backnang

Dr. Frank van den Bogaart
TNO Defence, Security and Safety, The Hague (NL)

Prof. Dr. Christian Boit
Technische Universität Berlin, Berlin (until 31.03.2013)

Dr. Thomas Fehn
Jenoptik AG, Jena

Prof. Dr. Claire Gmachl
Princeton University, Princeton (USA)

Dr. Ulf Meiners
United Monolithic Semiconductors GmbH, Ulm

Prof. Dr. Reinhart Poprawe M.A.
Fraunhofer-ILT, Aachen

Dr.-Ing. Christian Schmitz
TRUMPF Laser- & Systemtechnik GmbH, Ditzingen (as of 01.04.2013)

Berry Smutny
DELOS Space GmbH, Frankfurt am Main

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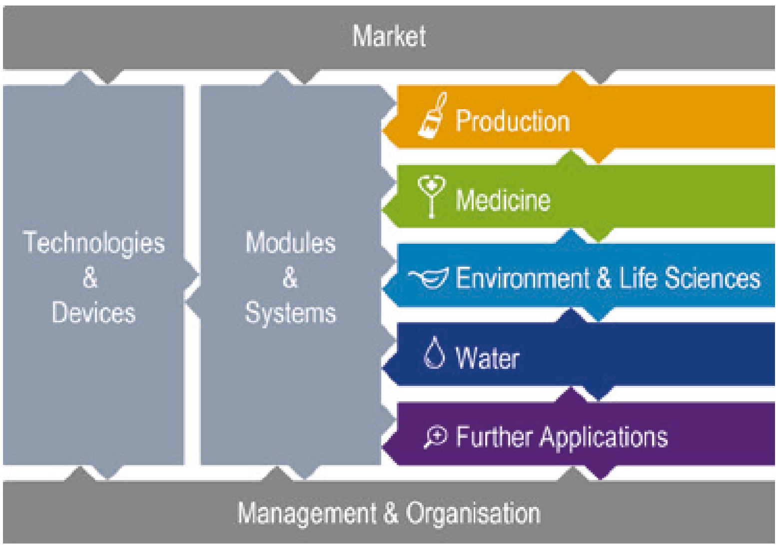
Highlights
Schlaglichter

Successful in the Zwanzig20 competition – Advanced UV for Life

Opening up innovative applications for ultraviolet (UV) light is the aim of „Advanced UV for Life". The association of research institutions and companies from various disciplines prevailed in the "Zwanzig20 – Partnership for Innovation" competition announced by the Federal Ministry of Education and Research (BMBF).

19 initial consortia were called upon to present their concepts – before, they were selected from 59 submitted initial concepts. Ten of which have been successful, among them "Advanced UV for Life". Aim of the consortium, coordinated by the Ferdinand-Braun-Institut, is to develop novel components, systems, and treatments based on UV light emitting diodes (LED). Applications are in medicine, water treatment, production technology, environment and life sciences. UV LEDs produce only little heat during operation, are extremely compact, and free from toxic substances. In addition, output power and wavelength can be adjusted freely. These light sources shall be used, among others, to purify potable water, to therapy skin diseases, and in the field of pipe renovation. "This approval is a great success for all institutions involved", reports Günther Tränkle, who represents the consortium as speaker. "Together we are able to consolidate our activities in the field of semiconductor-based UV light sources and make them accessible for a variety of applications – the right partners are on board at any rate, and we are open for further collaboration."

Currently, 23 partners bundle their competencies to research and develop novel semiconductor UV devices with tailored properties for specific applications. With that, the consortium will make an active scientific and technical contribution to solve the challenges of today's society and economy. These challenges will be addressed by interdisciplinary cooperation of developers and users of UV modules, systems, and equipment together with research partners and manufacturers of UV LEDs. The partners cover the entire value chain, from materials research to device manufacturing and systems integration up to the final application. Also, foundation of companies and adding further partners is planned.



Erfolgreich im Wettbewerb Zwanzig20 – Advanced UV for Life

Innovative Anwendungen von ultraviolettem (UV) Licht zu erschließen, darauf zielt „Advanced UV for Life". Der Zusammenschluss von Forschungseinrichtungen und Industrieunternehmen verschiedener Fachdisziplinen hat sich im Juli im Wettbewerb „Zwanzig20 – Partnerschaft für Innovation" des Bundesministeriums für Bildung und Forschung (BMBF) durchgesetzt.

19 Initialkonsortien waren aufgerufen, ihr Konzept zu präsentieren – diese waren zuvor aus 59 eingereichten Initialkonzepten ausgewählt worden. Zehn davon waren erfolg-

reich, darunter „Advanced UV for Life“. Ziel des vom Ferdinand-Braun-Institut geführten Konsortiums ist es, neuartige Komponenten, Systeme und Verfahren, die auf UV-Leuchtdioden (LED) basieren, für Anwendungen in Medizin, Wasserbehandlung, Produktionstechnik, Umwelt und Life Sciences zu entwickeln. UV-LEDs erzeugen im Betrieb wenig Wärme, sind extrem kompakt und frei von toxischen Stoffen. Leistung und Wellenlänge können dabei prinzipiell frei eingestellt werden. Diese Lichtquellen sollen künftig unter anderem für die Reinigung von Trinkwasser, die Therapie von Hautkrankheiten und im Bereich der Rohrsanierung eingesetzt werden. „Die Zusage ist ein großer Erfolg für alle beteiligten Institutionen“, erklärte Günther Tränkle, der das Konsortium als Sprecher vertritt. „Gemeinsam können wir nun unsere Aktivitäten im Bereich der halbleiterbasierten UV-Lichtquellen verstetigen und diese für vielfältige Anwendungen nutzbar machen – die richtigen Partner sind jedenfalls an Bord, und wir sind offen für weitere Kooperationen.“

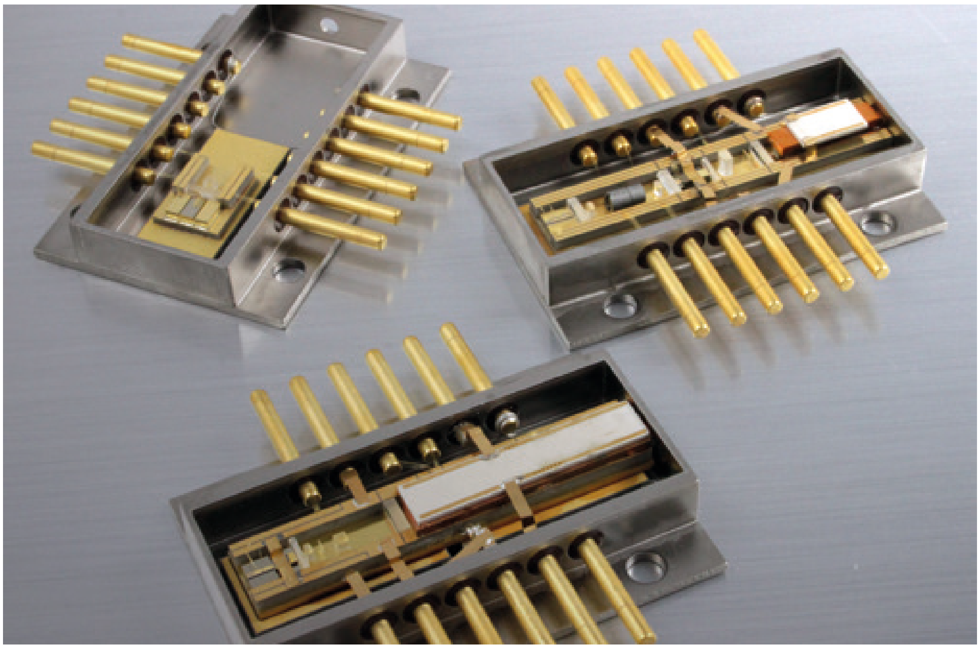
23 Partner bündeln derzeit ihre Kompetenzen, um neuartige Halbleiter-UV-Bauelemente mit maßgeschneiderten Eigenschaften und Applikationen zu erforschen und zu entwickeln. Damit wollen sie entscheidende wissenschaftlich-technische Beiträge zur Lösung von Herausforderungen in Gesellschaft und Wirtschaft leisten. Diese Herausforderungen sollen durch die interdisziplinäre Kooperation von Entwicklern und Anwendern von UV-Modulen, Systemen und Geräten sowie Forschungspartnern und Herstellern von UV-LEDs gelöst werden. Die Partner decken die gesamte Wertschöpfungskette ab, von der Materialforschung über Bauelementherstellung und Systemintegration bis zur Endanwendung. Auch Firmengründungen sowie die Aufnahme weiterer Partner sind vorgesehen.

Targeting Far East

In the past year, the FBH successfully expanded its international network. Apart from comprehensive cooperation in Europe and projects in the United States, the Asian region turned out to be an important market for the institute. In cooperation with Korean research and industrial partners, for example, first red and green laser sources have been assembled at the FBH. They shall be used as RGB light sources in future holographic television enabling an entirely new viewing experience (see subsequent article). Also in the field of display technology, the spin-off company Brilliance Fab Berlin has been established in 2013. The company is financed by Chinese partners, but located in close proximity to the FBH in Berlin Adlershof (further information about this spin-off, see p. 27). Together with two Taiwanese universities, the FBH develops both powerful miniaturized light sources for the yellow spectral region and GaN power transistors for green-IT solutions, which consume less energy or use it more efficiently.

Korea – realistic 3D television entertainment due to novel laser sources
Those who sit in front of their television screens in the future, will have the impression to meet their movie heroes within reach, three-dimensional and in the middle of the room. Without special glasses and with even better sharpness and improved effect of depth. This is the vision of the electronics group LG. To make it become real, the Korean company joined forces with top-class research institutions to develop the necessary special laser technology. Within the DisKo project, managed by the Korea Electronics Technology Institute (KETI), LG also cooperates with the Ferdinand-Braun-Institut. The FBH will develop the required red, green, and blue laser beam sources.

The technological leap in the 3D effect shall be possible by holography. Precondition for this technology is particularly good laser light delivering the required coherence and output power. To achieve this, FBH scientists use diode lasers with integrated gratings serving as wavelength filters. The light for the red spectral region around 650 nm can be generated directly – the respective chips are currently being tested at the FBH. As they emit only around 50 mW, the FBH uses optical amplifiers that are developed in parallel. Finally, a small module the size of a matchbox shall be available, comprising the semiconductor chips and the necessary microoptics to emit a highly coherent laser beam in the watt range. For green and blue laser radiation, the FBH uses its comprehensive know-how in the development of powerful beam sources in the near infrared. Their wavelength is transformed into the visible spectral region by using non-linear crystals. Modules emitting green laser radiation have already been assembled. Currently, the FBH team works on improving both the electro-optical efficiency of the semiconductor chips and the heat dissipation. As a result, the modules can be further miniaturized. The laser beam sources must eventually become so small and efficient that the television neither bursts the dimensions of a living room nor strains the energy bill.



< High-performance diode laser modules for display technology.
Leistungsfähige Diodenlaser-Module für die Displaytechnologie.

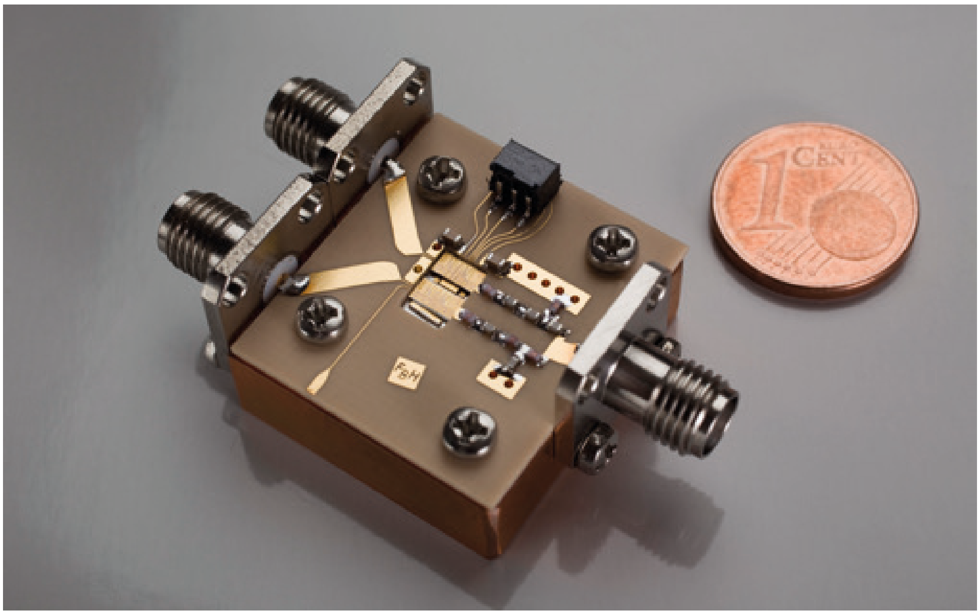
Taiwan – yellow light sources and energy-efficient power amplifiers
The cooperation with the National Taiwan University is developing dynamically: In December 2012, it all started out with an invited lecture held by Katrin Paschke in Taipeh. This laid the foundation for a projected 3-months research stay of the FBH scientist at the National Taiwan University – in February 2014, the corresponding application of Katrin Paschke has been positively evaluated by the Alexander von Humboldt-Stiftung. The cooperation especially aims at spectrally tunable laser sources emitting in the yellow spectral range. As a result of the close professional exchange of both research partners, the capability of hybrid-integrated light sources in this spectral range shall be further increased. With improved designs and novel manufacturing techniques of crystals used for non-linear frequency conversion, output powers are to be boosted to the watt range. With these features, the miniaturized beam sources are suitable for applications in fields like ophthalmology, medical skin treatment, and time-resolved fluorescence spectroscopy.

Also in the field of power electronics, the FBH cooperates with a Taiwanese university, the National Chiao Tung University (NCTU) in Hsinchu. Aim of the collaboration that has been started in 2012 is to further develop energy-efficient power converters. The FBH has established a 3" GaN-on-SiC process to manufacture normally-off power transistors for voltage levels up to 1000 V. NCTU, for its part, has developed a reproducible technique to grow gallium nitride on cost-effective silicon, a method complementary to the FBH process. To combine the advantages of both technologies, as a first step the NCTU wafer were compared with the substrates used at FBH in a benchmarking process. Then, the partners developed an adapted technique for the growth of p-GaN gate layers, which are used by the FBH in several ongoing European and federal projects. The related process modules have been developed within several research stays: three scientists from the FBH were working altogether for several weeks on the spot in Taiwan. In turn, two NCTU scientists executed research for several weeks at the FBH. The results were so promising that a follow-up project already started in 2014. In addition to further research stays, also a guest lecture held by Joachim Würfl in Taiwan is planned.

Japan – FBH power amplifier successfully tested at NEC

Digital power amplifier (PA) concepts are highly attractive, especially when it comes to optimizing wireless infrastructure like mobile base stations. Their architecture is already fully digitized, except for the radio-frequency (RF) amplifier. However, processing all signals digitally up to the final stage would simplify the system set-up significantly, reducing space requirements and cost. In addition, digital PAs are more flexible in terms of signal frequency and are expected to reduce energy consumption when using modern mobile communication standards like 3G and 4G. This potential makes them particularly interesting for companies involved in the wireless market such as NEC in Japan. Given this background, joint experiments with NEC have been conducted in October 2013: Andreas Wentzel tested an H-bridge class-D PA, which has been developed and built at FBH, at the IT company in Tokyo. This visit was one further step in the cooperation between NEC and FBH that started in 2011 and is planned to be further expanded in the future.

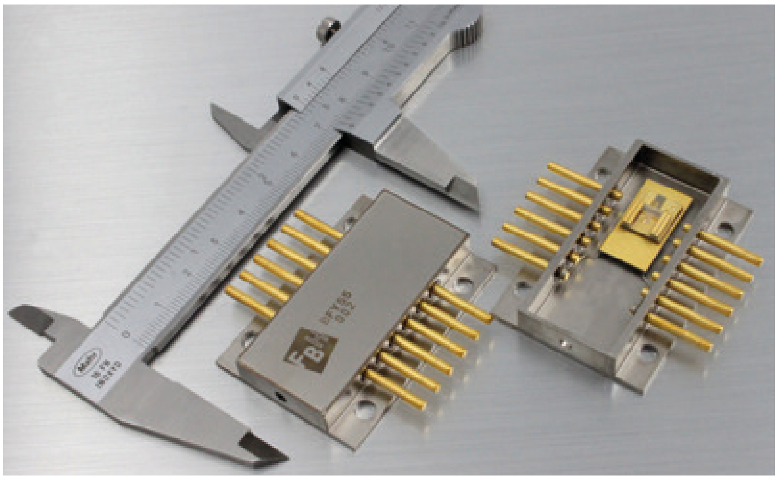
In the joint experiment, the Doherty concept was proven for digital signals the first time, successfully transferring it to the "digital world". So far, it has only been applied for analog input signals. The basic idea behind the Doherty approach is to operate two PAs in parallel – one of them is effectively only switched on at full-scale, which significantly enhances efficiency at power back-off. This is important because, according to modern communication standards, RF PAs in mobile base stations usually operate at 6…12 dB below full-scale at the input (power back-off). In the experiment, an FBH H-bridge PA 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 to 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, as it usually decreases very fast in this range.



< Class-D power amplifier for mobile communication base stations.
Klasse-D-Verstärker für Mobilfunkbasisstationen.

Fernost im Visier

Im vergangenen Jahr konnte das FBH seine internationale Vernetzung weiter ausbauen. Zu einem wichtigen Schwerpunkt hat sich, neben den umfassenden Kooperationen in Europa und Projekten in den USA, der asiatische Raum entwickelt. So wurden am FBH in Zusammenarbeit mit koreanischen Forschungs- und Industriepartnern erste rote und grüne Strahlquellen aufgebaut, die künftig als RGB-Laserlichtquellen in holografischen Fernsehgeräten zum Einsatz kommen sollen (siehe nachfolgender Artikel). Damit sollen vollkommen neuartige Seherlebnisse möglich werden. Ebenfalls im Bereich der Displaytechnologie wurde 2013 das Spin-off Brilliance Fab Berlin gegründet, das von chinesischen Partnern am Standort in Berlin-Adlershof finanziert wird (weitere Informationen zu dieser Ausgründung S. 28). Mit zwei taiwanesischen Universitäten entwickelt das FBH einerseits leistungsstarke, miniaturisierte Lichtquellen für den gelben Spektralbereich und andererseits GaN-Leistungstransistoren für Green-IT-Lösungen, die weniger Energie verbrauchen oder diese effizienter nutzen.



< Red-emitting diode laser modules for display technology.
Rot emittierende Diodenlaser-Module für die Displaytechnologie.

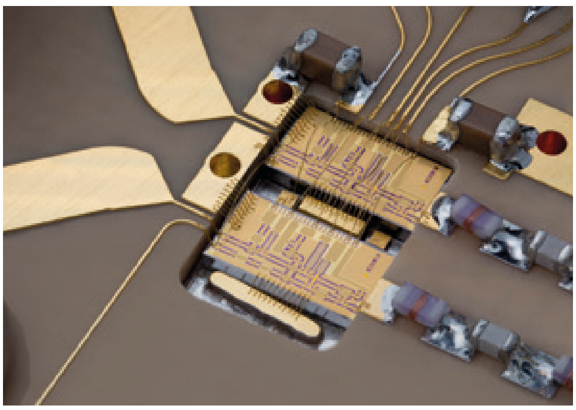
Korea – realitätsnaher 3D-Fernsehgenuss dank neuartiger Laserquellen
Wer künftig vor dem Fernseher sitzt, dem sollen die Filmhelden zum Greifen nah begegnen, dreidimensional und mitten im Raum. Ganz ohne Spezialbrille und mit noch besserer Schärfe und Tiefenwirkung. Das ist die Vision des Elektronikkonzerns LG. Um sie Realität werden zu lassen, hat sich das koreanische Unternehmen mit hochkarätigen Forschungsinstitutionen zusammengetan, die die hierfür benötigte spezielle Lasertechnologie entwickeln. Im Projekt DisKo, geleitet vom Korea Electronics Technology Institute (KETI), kooperiert LG dazu auch mit dem Ferdinand-Braun-Institut, das die passenden roten, grünen und blauen Laserstrahlquellen entwickelt.

Der Technologiesprung im 3D-Effekt soll durch Holografie möglich werden. Das funktioniert aber nur mit sehr gutem Laserlicht, das die nötige Kohärenz und Leistung besitzt. Dazu nutzen die FBH-Wissenschaftler Diodenlaser mit integrierten Gittern, die als Wellenlängenfilter dienen. Das Licht für den roten Spektralbereich um 650 nm kann direkt aus dem Halbleiterchip erzeugt werden – entsprechende Chips werden am FBH derzeit getestet. Da diese nur circa 50 mW emittieren, werden parallel dazu optische Verstärker entwickelt. Endziel ist ein kleines Modul von der Größe einer Streichholzschachtel, das die Halbleiterchips und die notwendigen Mikrooptiken enthält, um einen Laserstrahl hoher Kohärenz im Wattbereich zu emittieren. Für die grüne und blaue Laserstrahlung nutzt das FBH sein Know-how bei leistungsstarken Strahlquellen im nahen Infrarot. Deren Wellenlänge wird mithilfe von nichtlinearen Kristallen in den sichtbaren Spektralbereich transformiert. Module mit grüner Laserstrahlung wurden bereits aufgebaut. Zurzeit arbeitet das FBH-Team daran, den elektrooptischen Wirkungsgrad der Halbleiterchips und die Wärmeabfuhr *zu verbessern. Dadurch lassen sich die Module weiter miniaturisieren. Die Laserlichtquellen müssen schließlich so klein und effizient sein, dass die Fernseher ins Wohnzimmer passen und sie die Energierechnung nicht belasten.*

Taiwan – gelbe Lichtquellen und energieeffiziente Leistungsverstärker

Dynamisch entwickelt sich derzeit die Kooperation mit der National Taiwan University. Begonnen hatte diese im Dezember 2012 mit einem Vortrag, zu dem Katrin Paschke nach Taipeh eingeladen wurde. Das legte den Grundstein für einen geplanten Forschungsaufenthalt der FBH-Wissenschaftlerin an der National Taiwan University – ein entsprechender Antrag für ein 3-monatiges Forschungsstipendium des National Science Council Taiwan wurde im Februar 2014 von der Alexander von Humboldt-Stiftung positiv evaluiert. In der Kooperation geht es vor allem um spektral durchstimmbare Laserquellen, die im gelben Spektralbereich emittieren. Durch den engen fachlichen Austausch der beiden Forschungspartner soll die Leistungsfähigkeit von hybrid-integrierten Lichtquellen in diesem Spektralbereich weiter erhöht werden. Verbesserte Designs und neue Techniken bei der Herstellung von Kristallen zur nichtlinearen Frequenzkonversion sollen die Ausgangsleistungen in den Wattbereich steigern. Damit eignen sich die miniaturisierten Strahlquellen für Anwendungen in Bereichen wie der Augenheilkunde, zur medizinischen Hautbehandlung oder zeitaufgelösten Fluoreszenzspektroskopie.

Auch im Bereich der Leistungselektronik kooperiert das FBH mit einer taiwanesischen Hochschule, der National Chiao Tung University (NCTU) in Hsinchu. Ziel der 2012 gestarteten Zusammenarbeit ist es, GaN-Leistungstransistoren für energieeffiziente Leistungskonverter gemeinsam weiterzuentwickeln. Das FBH verfügt über einen etablierten 3" GaN-auf-SiC-Prozess zur Fertigung von Normally-off-Leistungstransistoren für Spannungslevels bis 1000 V. Die NCTU hat ihrerseits eine reproduzierbare Technik etabliert, mit der sich Galliumnitrid auf kostengünstigem Silizium aufwachsen lässt – eine komplementäre Methode zum FBH-Verfahren. Um die Vorteile beider Technologien verknüpfen zu können, wurden zunächst die NCTU-Wafer mit den am FBH verwendeten Substraten in einem Benchmarking-Prozess verglichen. Anschließend entwickelten die Partner eine angepasste Technik zum Wachstum von p-GaN-Gate-Schichten, die das FBH in mehreren laufenden EU- und BMBF-Projekten nutzt. Die zugehörigen Prozessmodule wurden im Rahmen mehrerer Forschungsaufenthalte entwickelt, bei denen zwei Wissenschaftler und eine Wissenschaftlerin des FBH im vergangenen Jahr insgesamt mehrere Wochen vor Ort in Taiwan arbeiteten. Im Gegenzug forschten zwei NCTU-Wissenschaftler mehrere Wochen am FBH. Die Ergebnisse waren so vielversprechend, dass 2014 bereits ein Folgeprojekt startete. Neben weiteren Forschungsaufenthalten ist auch eine Gastvorlesung von Joachim Würfl in Taiwan geplant.



∧ Chips (detail) of the class-D power amplifier module for mobile communication base stations.
Chips (Detail) des Klasse-D-Leistungsverstärkers für Mobilfunkbasisstationen.

Japan – FBH-Leistungsverstärker erfolgreich bei NEC getestet

Digitale Verstärkerkonzepte sind für die Industrie überaus attraktiv, unter anderem um Mobilfunkbasisstationen zu optimieren. Deren Infrastruktur ist bis auf den Sendeverstärker bereits digitalisiert. Wenn jedoch alle Signale bis zur Endstufe digital verarbeitet werden, vereinfacht dies die Architektur im Vergleich zu analogen Sendeverstärkern. Das senkt den Platzbedarf und die Kosten. Zudem sind digitale Verstärker flexibler hinsichtlich der Signalfrequenz und versprechen Energieeinsparungen bei modernen Mobilfunkstandards wie 3G oder 4G. Dieses Potenzial macht sie für Unternehmen wie NEC in Japan attraktiv. In diesem Kontext testete Andreas Wentzel im Oktober 2013 beim IT-Konzern in Tokio einen vom FBH entwickelten und gefertigten Klasse-D-Verstärker in H-Brücken-Topologie. Das festigte zugleich die bereits seit 2011 bestehende Kooperation, die künftig noch ausgebaut werden soll.

Mit dem gemeinsamen Experiment wurde erstmals das digitale Doherty-Konzept erprobt, das bislang nur bei analogen Eingangssignalen angewendet wurde. Durch den parallelen Betrieb zweier Verstärker, von denen einer effektiv nur im Bereich der Vollaussteuerung hinzugeschal-

tet wird, kann der Wirkungsgrad bei geringeren Leistungen angehoben werden. Dies wird nötig, da bei Nutzung moderner Mobilfunkstandards die Leistungsverstärker in den Basisstationen heutzutage typischerweise 6…12 dB unterhalb der Vollaussteuerung betrieben werden. Im Experiment wurde eine H-Brücken-Schaltung aus dem FBH mit einem von NEC gefertigten Envelope-Delta-Sigma-Modulator betrieben. Damit konnte das Doherty-Konzept erstmals erfolgreich auf die „digitale Welt" übertragen werden. Bei Betrieb zwischen 6 dB und 12 dB unterhalb der Vollaussteuerung zeigte der Verstärker bis zu 20 % mehr Effizienz verglichen mit herkömmlich betriebenen, balancierten digitalen Verstärkern. Für breitbandige Signale moderner Modulationsverfahren wie etwa WCDMA liegt die Verbesserung immerhin noch bei etwa 10 %. Aktuelles Entwicklungsziel ist es nun, die Verstärkereffizienz für den Betrieb von mehr als 10 dB unterhalb der Vollaussteuerung weiter zu verbessern, da diese dann üblicherweise schnell abfällt.

Founding spirit – three new spin-offs in 2013

^ Xiaozhuo Wang – founder of Brilliance Fab Berlin.
Xiaozhuo Wang – Gründer von Brilliance Fab Berlin.

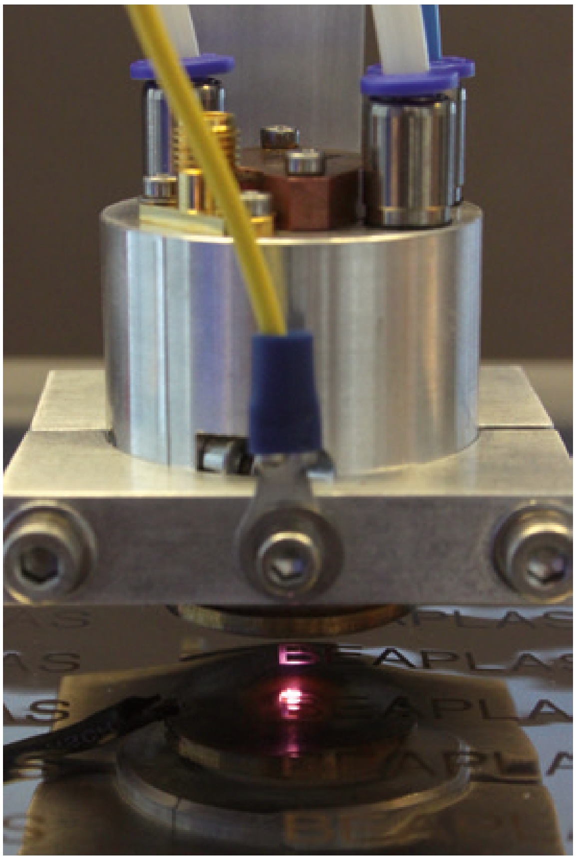
Close cooperation of FBH with industrial partners, research institutions, and universities ensures quick transfer of results into application. The institute has been awarded already several times for its successful technology transfer – a similar effect can be observed in the field of spin-offs: FBH's R&D activities yielded already nine companies, three of them added in the last year.

Brilliance Fab Berlin – laser modules from German-Chinese cooperation
Capturing the Chinese market for display applications with semiconductor technology developed by the FBH is the aim of Brilliance Fab Berlin GmbH & Co. KG (BFB). The company was founded as a result of the collaboration between the Ferdinand-Braun-Institut and the Chinese partner Sino Nitride Semiconductor CO., LTD (SNS). SNS plans to invest 2.2 million Euros in its German subsidiary within the first two years.

At the FBH, compact diode laser modules for applications in displays have been developed in recent years. This technology will now be further advanced for direct use in industry by two former FBH scientists, Xiaozhuo Wang and Sven Schwertfeger, within the spin-off BFB. Laser diodes are therefore assembled with holographic gratings, lenses, mirrors, and further optical elements to extremely compact modules. For a start, the laser technology for the modules targeting the Chinese market will be developed at the Adlershof site. Once the demonstrator is ready for manufacturing, large-scale production in China shall commence. SNS already projects a Chinese production facility. The technology will then constantly be further improved by BFB in Germany. On the long run, completely new diode laser modules shall be investigated and developed by the FBH within the scope of research assignments. Another main pillar of the young company is sales and distribution of SNS products throughout Europe including, for example, gallium nitride substrates and LED illumination.

Phasor Instruments – open source meets measurement technology
For Phasor Instruments UG it is all about network analyses and the development of measurement devices for microwave technology. The entrepreneur behind the spin-off founded in May 2013 is Silvio Kühn. Already during his Ph.D., the engineer for computer engineering dealt with microwave plasma sources and innovative measurement methods. To accomplish the essential R&D work, Silvio Kühn is supported by the EXIST-Forschungstransfer program for one year.

Meanwhile, the first prototype of his Synthesizer Vector Receiver (SVR) is available. This generator produces a microwave signal in the gigahertz range suitable to excite and characterize plasmas. The network analyzer can be programmed with control algorithms helping to generate a stable plasma with defined characteristics. Kühn's business model



^ Compact microwave plasma source for surface activation.
Kompakte Mikrowellen-Plasmaquelle zur Oberflächenaktivierung.

fully relies on open source software. This way, the client is not bound to definite software licenses and can therefore customize the equipment very flexibly according to the actual specific needs. The application fields of the network analyzer range from controlled heating tasks to coating processes in semiconductor industry. In contrast to standard measurement equipment, the SVR is significantly more compact, more cost-efficient, and more versatile. Further devices are currently under development. Even a first customer could already be acquired, a long-term cooperation partner of the FBH seeking to solve a complex measurement and control problem.

BEAPLAS – deposition of thin layers at atmospheric pressure
BEAPLAS GmbH develops and markets processes and devices to produce thin layers at atmospheric pressure. A plasma source that can be operated at ambient air is the crucial tool for such tasks. This source has been developed at the FBH within the last years and has been optimized for various applications, from automotive manufacturing to medical technology. Currently, mostly complex vacuum technology is used, which makes the straightforward and cost-efficient atmospheric processes also commercially attractive. The spin-off that was founded in May 2013 is funded within the EXIST-Forschungstransfer program over a 1.5 years period.

A first prototype is already offered by the spin-off headed by the FBH scientist and managing director Roland Gesche. The device deposits gold layers at technically relevant deposition rates by applying microwave power to a gold wire, which then results in a plasma. This way, the sputtered gold can be deposited onto surfaces producing coatings in the nanometer range. In particular, electronic devices profit from this treatment, as the process enables to produce good conductibility also for selective areas – required, for example, for relay contacts.

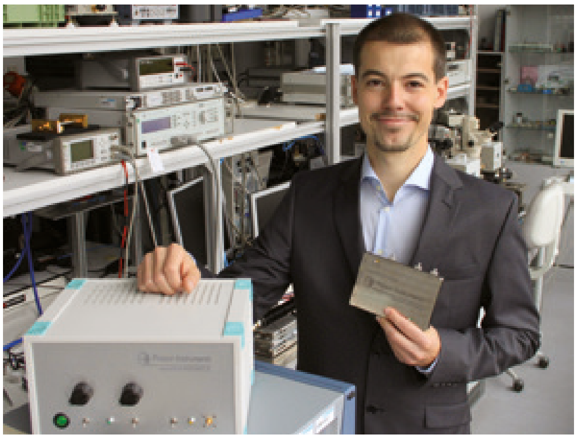
Gründerstimmung – drei neue Ausgründungen in 2013

Die enge Zusammenarbeit des FBH mit Industriepartnern, Forschungseinrichtungen und Universitäten garantiert die schnelle Umsetzung der Ergebnisse in die Praxis. Für seinen erfolgreichen Technologietransfer wurde das Institut bereits mehrfach ausgezeichnet, ebenso beispielgebend verhält es sich im Bereich der Ausgründungen: Neun Spin-offs hat das FBH inzwischen hervorgebracht, drei Ausgründungen sind alleine im letzten Jahr hinzugekommen.

Brilliance Fab Berlin: Lasermodule aus deutsch-chinesischer Zusammenarbeit
Die am FBH entwickelte Halbleiterlaser-Technologie, soll künftig den chinesischen Markt für Displayanwendungen erobern. Mit diesem Ziel wurde die Brilliance Fab Berlin GmbH & Co. KG (BFB) im Rahmen der Kooperation zwischen dem Ferdinand-Braun-Institut und dem chinesischen Unternehmen Sino Nitride Semiconductor CO., LTD (SNS) gegründet. 2,2 Millionen Euro investiert SNS in den ersten zwei Jahren in die deutsche Tochter.

Am FBH wurden in den vergangenen Jahren kompakte Diodenlasermodule für den Einsatz in Displays entwickelt. Diese Technologie entwickeln nun zwei ehemalige FBH-Wissenschaftler, Xiaozhuo Wang und Sven Schwertfeger, beim Spin-off BFB für den unmittelbaren Einsatz in der Industrie weiter. Dazu werden die Laserdioden mit holographischen

Gittern, Linsen, Spiegeln und anderen optischen Elementen zu extrem kompakten Modulen aufgebaut. Die Lasertechnologie der Module für den chinesischen Markt wird zunächst am Standort Adlershof entwickelt. Sobald der produktionsreife Demonstrator fertig ist, soll die Volumenproduktion in China starten. SNS plant bereits eine Fertigungsstätte im eigenen Land. Die Technologie soll dann von BFB in Deutschland immer weiter verbessert werden. Langfristig sollen auch vollständig neue Diodenlasermodule im Rahmen von Forschungsaufträgen am FBH erforscht und entwickelt werden. Ein weiteres Standbein des jungen Unternehmens ist der europaweite Vertrieb von SNS-Produkten, wie etwa Galliumnitrid-Substraten und LED-Beleuchtungen.



^ Silvio Kühn with his prototype network analyzer.
Silvio Kühn mit dem Prototyp seines Netzwerkanalysators.

Phasor Instruments: Open Source trifft Messtechnik

Bei der Phasor Instruments UG dreht sich alles um Netzwerkanalyse und die Entwicklung von Messgeräten für die Mikrowellentechnik. Der Unternehmer hinter dem im Mai 2013 gegründeten Spin-off ist Silvio Kühn. Bereits im Rahmen seiner Promotion am FBH hatte sich der Ingenieur der Technischen Informatik mit Mikrowellen-Plasmaquellen und innovativen messtechnischen Verfahren beschäftigt. Um die erforderlichen Entwicklungsarbeiten durchführen zu können, wird er ein Jahr lang im Rahmen des EXIST-Forschungstransfers gefördert.

Inzwischen gibt es bereits den ersten Prototypen seines Synthesizer Vector Receiver (SVR). Dieser Generator erzeugt ein Mikrowellensignal im Gigahertz-Bereich, mit dem Plasmen angeregt und charakterisiert werden können. In den Netzwerkanalysator lassen sich Regelalgorithmen einprogrammieren, die helfen, ein stabiles Plasma mit ganz bestimmten Eigenschaften zu erzeugen. Kühn setzt bei seinem Geschäftsmodell auf Open Source. Damit ist der Auftraggeber nicht an bestimmte Software-Lizenzen gebunden, und das Gerät kann flexibel entsprechend der Kundenerfordernisse entwickelt und später weiter angepasst werden. Die Anwendungsgebiete des Netzwerkanalysators reichen von kontrollierten Erwärmungsaufgaben bis hin zu Beschichtungsprozessen in der Halbleiterindustrie. Im Gegensatz zu herkömmlichen Messgeräten ist der SVR wesentlich kompakter, kostengünstiger und flexibler einsetzbar. Weitere Geräte sind in der Entwicklung. Auch einen ersten Auftraggeber konnte Kühn bereits gewinnen, einen langjährigen Kooperationspartner des FBH, der nach der Lösung für ein komplexes mess- und regelungstechnisches Problem suchte.

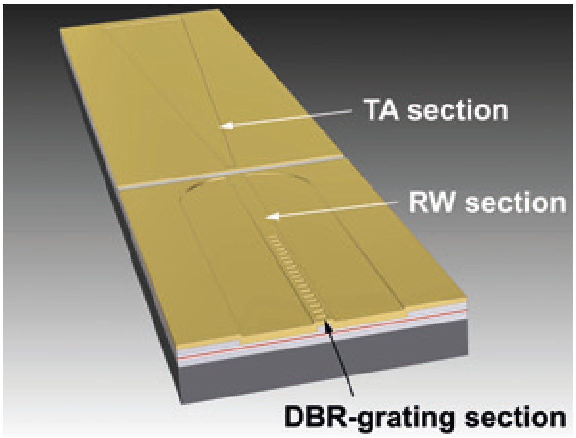
BEAPLAS: dünne Schichten bei Atmosphärendruck abscheiden

Die BEAPLAS GmbH entwickelt und vertreibt Verfahren und Geräte zur Herstellung dünner Schichten bei Atmosphärendruck. Zentrales Werkzeug ist eine Plasmaquelle für den Betrieb an der Umgebungsluft, die in den letzten Jahren am FBH entwickelt und für verschiedene Applikationen – vom Automobilbau bis zur Medizintechnik – optimiert wurde. Da zurzeit meist aufwändige Vakuumtechnik verwendet wird, sind kostengünstigere Atmosphärenprozesse kommerziell attraktiv. Das Spin-off, im Mai 2013 gegründet, wird im Rahmen von EXIST-Forschungstransfer über einen Zeitraum von 1,5 Jahren gefördert.

Einen ersten Prototyp, der Goldschichten mit technisch relevanten Abscheidungsssraten liefert, kann das Spin-off rund um FBH-Wissenschaftler und Gründungsgeschäftsführer Roland Gesche bereits vorweisen. Mikrowellenleistung wird dazu an einen Golddraht angelegt. Dabei entsteht ein Plasma. Mithilfe dieses ionisierten Gases wird das Gold in der Plasmawolke zerstäubt. Das zerstäubte Gold kann dann auf Oberflächen abgeschieden werden, um Beschichtungen im Nanometerbereich herzustellen. Das ist für elektronische Bauteile wichtig, denn mit dem Verfahren lässt sich eine gute Leitfähigkeit auch für punktuelle Flächen erzeugen, etwa bei Relais-Kontakten.

Spotlight on laser sensors – diode lasers, systems & applications

When it comes to materials analysis in medicine, food industry, and semiconductor technology laser sensors are gaining in importance. Thus, the FBH develops miniaturized beam sources for applications in spectroscopy in an abundance of projects – with a continued upward trend. The depth of FBH's R&D expertise ranges from semiconductor chips to laser beam sources to measurement systems and increasingly involves the specific application. Foundation for this advancement is the technology being available at the FBH, which allows the institute to manufacture tailored wavelength-stabilized diode lasers with monolithic-integrated gratings.



∧ Tapered laser developed within FAMOS – combines excellent beam quality with high output power.
Trapezlaser im Projekt FAMOS – kombiniert exzellente Strahlqualität mit hoher Ausgangsleistung.

FBH's uses a flexible process based on e-beam lithography to generate such gratings (see specialist article p. 90). With it, the institute realizes spectrally stabilized beam sources from the red (635 nm) to the near infrared (1180 nm) spectral region. This process is also suitable to fabricate such diode lasers in large quantities. It is applied in various R&D projects in the area of laser sensors, for Raman spectroscopy as well as for the development of diode lasers used for fluorescence spectroscopy like in the InnoProfile transfer project YELLOW. The same applies to the EU-funded FAMOS project, where a small narrow spectral linewidth of the light sources is decisive to pump femtosecond titan-sapphire lasers. Both projects rely on frequency doubling, either to stimulate samples in the yellow wavelength range from 550 nm to 590 nm (YELLOW) or to pump titan-sapphire laser crystals at 515 nm (FAMOS). Due to these miniaturized beam sources, equipment becomes mobile and less expensive – and this is what makes the FBH lasers a key part for these applications in medical diagnostics.

Raman spectroscopy – the basis for precise analytics

Raman spectroscopy is ideally suited if one wants to characterize materials very exactly. With this optical analysis method biological, chemical, and pharmaceutical samples can be determined contact-free and extremely precisely. A sample is irradiated for this purpose with monochromatic laser light which is then scattered back differently, depending on the respective substance. The result is as unique as a fingerprint, and thus making Raman spectroscopy particularly attractive for trace analysis and applications in the health and food monitoring field.

However, there are obstacles to overcome that the FBH addresses with tailored solutions. Raman lines, for example, can be superimposed by a several orders of magnitude greater fluorescence spectrum or background light like daylight and room illumination. **S**hifted **E**xcitation **R**aman **D**ifference **S**pectroscopy (SERDS) offers a solution for this problem by exciting the sample with light emitted at two closely neighboring frequencies. As a result, the fluorescence changes only slightly, but the Raman lines shift and can be separated from stray light. Thus, this measurement method improves the detection limit by more than one order of magnitude compared to conventional Raman spectroscopy. Meanwhile, this approach is applied in several projects:

<u>Two-wavelength diode lasers</u>

In the BMBF-funded project DiLaRa the focus is on the development of novel chips and a compact optical system. The FBH designs special diode lasers which generate the two wavelengths required for SERDS in only one chip. This is achieved by two separately selectable sections in the laser and gratings implemented into the semiconductor chip. As a consequence, this approach makes light sources much more compact and thus enables miniaturized, portable laser measurement systems. With them,

∧ Assessing fruit characteristics in-situ by multispectral sensing.
In-situ-Messung von Fruchteigenschaften mittels eines Multispektral-Sensors.

in-situ measurements in various security and health-relevant areas of biology, medicine, food control, and pharmacy can be executed in the future. In addition, further applications are conceivable for this concept including absorption spectroscopy and generation of terahertz radiation.

Portable Raman system for gardening

Within the EU-funded project USER-PA (**US**ability of **E**nvironmentally sound and **R**eliable techniques in **P**recision **A**griculture) international partners from various research disciplines joined forces to develop a sustainable technological platform for precision gardening. Producers will then have access to gapless and reliable information on growth-relevant parameters and the degree of ripeness of fruits. First field tests are planned in the field of fruit growing.

The FBH develops a suitable novel and portable Raman sensor system, building up on developments achieved within the DiLaRa project. Within USER-PA, the usability of such a two-wavelength system for Raman spectroscopy shall be explored in the agricultural sector. Aim is to obtain data regarding soil characteristics, watering of plants, and supply of nutrients as well as to determine the ideal harvest time. It will accordingly be possible to react on changing environment conditions directly and to utilize water and energy efficiently and resource-friendly.

HautScan – non-invasive diagnostics with lasers

Within the Einstein research project HautScan, TU Berlin and FBH develop a non-invasive optical method to detect substances on the skin. Doctors from the Charité contribute with the necessary medical know-how. The project was motivated by the hand foot syndrome which often occurs during cancer therapy. When treating patients with the chemotherapeutic substance doxorubicin, the medication first passes through the skin and then penetrates it again. The therapeutic agent therefore affects the skin and often leads to discontinuation of therapy. To avoid this and to ensure timely and targeted treatment, the chronological processes during administration of doxorubicin shall be monitored very carefully by means of optical methods.

The suitable light sources and the complete optical system are currently being developed at the FBH. This light source is based on frequency-doubled diode lasers – this means that their wavelength is bisected by non-linear frequency conversion. The optical system comprises the excitation source emitting the light at the skin and a spectrometer collecting the Raman photons scattered back. This equipment subsequently interprets the collected information.

Lasersensorik im Fokus – Diodenlaser, Systeme & Applikationen

Bei der Untersuchung von Materialien in der Medizin, Nahrungsmittelindustrie und Halbleitertechnik gewinnt die Lasersensorik zunehmend an Bedeutung. In einer Fülle von Projekten entwickelt das FBH miniaturisierte Strahlquellen für den Einsatz in der Spektroskopie – mit weiter steigender Tendenz. Die Entwicklungstiefe geht vom Halbleiterchip über Laserstrahlquellen bis zu Messsystemen und zunehmend auch hin zu konkreten Applikationen. Die Basis hierfür ist die am FBH verfügbare Technologie, um maßgeschneiderte wellenlängenstabilisierte Diodenlaser mit monolithisch integrierten Gittern herzustellen.

Zum Erzeugen der Gitter nutzt das FBH einen flexiblen Prozess, der auf der E-Beam-Lithografie basiert (siehe Fachartikel S. 90). Damit realisiert das Institut spektral stabilisierte Strahlquellen vom roten Spektralbereich (635 nm) bis ins nahe Infrarot (1180 nm). Dieser Prozess eignet sich auch für die Fertigung hoher Stückzahlen und wird in mehreren F&E-Vorhaben im Bereich der Lasersensorik genutzt: für die Ramanspektroskopie ebenso wie bei der Entwicklung von Diodenlasern für die Fluoreszenzspektroskopie, wie im InnoProfile-Transfer-Projekt YELLOW. Auch im EU-Projekt FAMOS ist der Prozess entscheidend, da Pumplichtquellen mit einer schmalen spektralen Linienbreite für Femtosekunden-Titan-Saphir-Laser benötigt werden. Diese dienen als Lichtquellen für die optische Kohärenztomographie. Beide Projekte nutzen zusätzlich die Frequenzverdopplung, um Proben im gelben Wellenlängenbereich bei 550 nm bis 590 nm anzuregen (YELLOW) oder Titan-Saphir-Laserkristalle bei 515 nm zu pumpen (FAMOS). Durch diese miniaturisierten Strahlquellen werden die Geräte mobil einsetzbar und preiswerter. Das macht die FBH-Laser zu einem Kernstück für diese Anwendungen in der medizinischen Diagnostik.

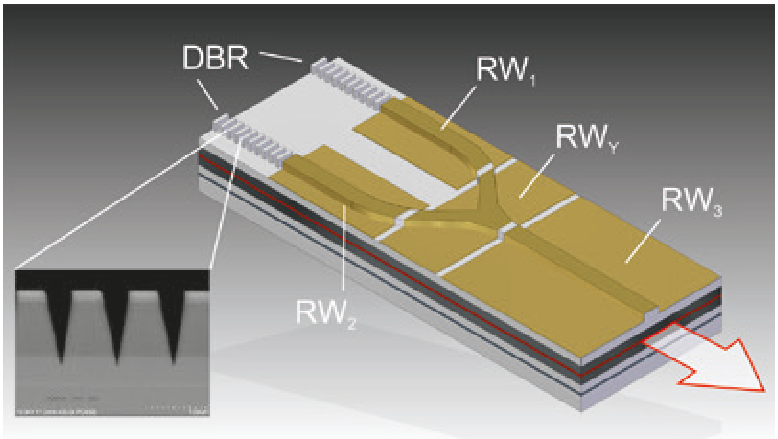
Raman-Spektroskopie – Basis für präzise Analytik

Geht es um die exakte Charakterisierung von Materialien, ist die Raman-Spektroskopie das ideale Verfahren. Mit der optischen Analysemethode lassen sich biologische, chemische und pharmazeutische Proben berührungsfrei und sehr präzise bestimmen. Dabei wird eine Probe mit monochromatischem Laserlicht bestrahlt, das je nach Substanz unterschiedlich zurückgestreut wird. Das Resultat ist so einmalig wie ein Fingerabdruck. Dies macht die Raman-Spektroskopie besonders attraktiv für die Spurenanalytik und Anwendungen im Bereich der Gesundheit und Lebensmittelüberwachung.

*Dennoch gibt es Hürden. Um diese zu überwinden, entwickelt das FBH maßgeschneiderte Lösungen. So können Raman-Linien beispielsweise von einem um mehrere Größenordnungen stärkeren, breiten Fluoreszenzspektrum oder Hintergrundlicht, etwa Tageslicht oder Raumbeleuchtung, überdeckt werden. Hier liefert die **S**hifted **E**xcitation **R**aman **D**ifference **S**pectroscopy (SERDS) einen Ausweg. Dazu wird die Probe mit zwei dicht beieinanderliegenden Frequenzen angeregt. Die Fluoreszenz ändert sich dadurch kaum – aber die Raman-Linien verschieben sich und lassen sich vom Störlicht trennen. Die Nachweisgrenze gegenüber der herkömmlichen Raman-Spektroskopie kann mit dieser Messmethode um mehr als eine Größenordnung verbessert werden. Dieser Lösungsansatz kommt inzwischen bei mehreren Projekten zum Einsatz:*

<u>Zwei-Wellenlängen-Diodenlaser</u>

Im BMBF-geförderten Vorhaben DiLaRa stehen die Entwicklung neuartiger Chips und eines kompakten optischen Systems im Mittelpunkt. Das FBH designt dafür spezielle Diodenlaser, die die für SERDS notwendigen zwei Wellenlängen in nur einem Chip erzeugen. Dies erfolgt über zwei separat ansteuerbare Sektionen im Laser und in den Halbleiterchip implementierte Gitter. Die Lichtquellen werden dadurch deutlich kompakter und ermöglichen miniaturisierte, portable Lasermesssysteme. Damit können künftig Vor-Ort-Messungen in verschiedenen sicherheits- und gesundheitsrelevanten Bereichen der Biologie, Medizin, Lebensmittelkontrolle und Pharmazie durchgeführt



∧ Two-wavelength diode laser for Raman spectroscopy.
Zwei-Wellenlängen-Diodenlaser für die Raman-Spektroskopie.

werden. Darüber hinaus sind für das Konzept weitere Anwendungen, unter anderem in der Absorptions-Spektroskopie und zur Erzeugung von Terahertz-Strahlung, denkbar.

Portables Raman-System für den Gartenbau

*Im EU-Projekt USER-PA (**US**ability of **E**nvironmentally sound and **R**eliable techniques in **P**recision **A**griculture) haben sich internationale Partner verschiedenster Forschungsdisziplinen zusammengetan, um eine zukunftsfähige und nachhaltige technologische Plattform für den Präzisionsgartenbau zu schaffen. Damit sollen sich Produzenten künftig lückenlos und verlässlich über wachstumsentscheidende Parameter und den Reifegrad von Früchten informieren können. Erste Feldversuche sind im Bereich des Obstbaus geplant.*

Das FBH entwickelt dafür ein neuartiges portables Raman-Sensorsystem, das auf den Entwicklungen im Projekt DiLaRa aufbaut. Im Rahmen von USER-PA soll die Nutzbarkeit dieses Zwei-Wellenlängensystems für die Raman-Spektroskopie im landwirtschaftlichen Bereich erforscht werden. Ziel ist es, Daten zur Bodenbeschaffenheit, zur Versorgung von Pflanzen mit Wasser und Nährstoffen und zum idealen Erntezeitpunkt zu gewinnen. Damit soll es auch möglich werden, auf veränderte Umweltbedingungen direkt zu reagieren sowie Wasser und Energie effizient und ressourcenschonend einzusetzen.

HautScan – nicht-invasive Diagnostik mit Lasern

Im Rahmen des Einstein-Forschungsvorhabens HautScan entwickeln die TU Berlin und das FBH seit 2012 eine nichtinvasive optische Methode zum Nachweis von Substanzen auf der Haut. Das notwendige medizinische Know-how bringen Ärzte der Charité ein. Konkreter Anlass war das Hand-Fuß-Syndrom, das bei Krebspatienten häufig vorkommt: Bei der Behandlung mit dem Chemotherapeutikum Doxorubicin tritt das Medikament erst durch die Haut aus und dringt dann wieder in sie ein. Dadurch zerstört es die Haut und führt häufig zum Abbruch der Therapie. Um dies zu vermeiden und rechtzeitig gezielt behandeln zu können, sollen künftig die zeitlichen Abläufe bei der Behandlung mit Doxorubicin mithilfe rein optischer Verfahren genau kontrolliert werden.

Die passenden Lichtquellen und das komplette optische System werden derzeit am FBH entwickelt. Die Lichtquelle basiert auf frequenzverdoppelten Diodenlasern, deren Wellenlänge mittels nicht-linearer Frequenzkonversion halbiert wird. Das optische System beinhaltet die Anregungsquelle, die das Licht auf die Haut strahlt, sowie ein Spektrometer, das die zurückgestreuten Raman-Photonen einsammelt und diese Informationen anschließend auswertet.

∧ Miniaturized diode laser module for Raman spectroscopy emitting in the blue spectral range.
Miniaturisiertes Diodenlaser-Modul für die Raman Spektroskopie, das im blauen Spektralbereich emittiert.

Satellite communications – frictionless exchange of information under challenging conditions

The communication between satellites and to Earth is truly demanding with respect to the related technical requirements: Devices need to be particularly robust so that they can survive a rocket launch and the harsh conditions in space. Moreover, components cannot simply be maintained if they do no longer work properly. Thus, reliability plays a decisive role, and devices therefore have to proof their suitability for use in space in challenging stress tests.

The FBH has long-term and comprehensive experience with space applications. The institute cooperates, among others, since more than 15 years with Tesat-Spacecom, Europe's major supplier for equipment used in satellite communications, and works in projects with the European Space Agency ESA for many years. In optoelectronics as well as in the field of microwaves and power electronics, a variety of R&D projects deal with satellite communications. Since 2008, the newly implemented laser metrology group works on the development of laser modules for space-borne experiments. Meanwhile, a growing number of FBH devices from optoelectronics, microwaves, and power electronics are therefore space-qualified.

Diode lasers – core components for optical communications

An ever increasing amount of data is transferred worldwide. Satellites play an essential part that information is delivered reliably. Accordingly, the FBH faces an increasing demand for its space-qualified laser diode benches. Used as pump sources for highly efficient solid-state laser in laser communication terminals (LCT) of Tesat-Spacecom, they help ensuring smooth communication. LCTs are the centerpieces in optical communications of satellites, making sure that signals are transmitted over long distances via light. The data transfer rate when using light is significantly higher than with microwaves. With LCTs of the current generation a data amount of 1.8 gigabit per second can be transferred over a very long distance of 45,000 kilometers – this corresponds to the content of a standard DVD every 21 seconds. Due to this capability, transmission of data packages between satellites in near-Earth orbit between 200 and 2,000 kilometers height and those in geostationary orbit in around 36,000 kilometers height is possible. In addition, applications and services in the field of Earth observation can be significantly improved.

<u>Earth observation and distance measurement</u>

The compact, space-qualified laser diode benches from the Ferdinand-Braun-Institut are used, among others, in the European Sentinel Earth observation satellites. In a sort of data highway in space, information between the satellites shall be exchanged twenty-four-seven in the future. Several Sentinel satellites will then surround the Earth with high velocity – one circumnavigation takes around an hour and a half. In the meantime, the satellites take a large number of pictures from the Earth. All data collected shall be transmitted during the flyby to the Alphasat satellite and then to the geostationary satellites, transferring the images finally to the Earth.

FBH's lasers are additionally utilized in Tesat-Spacecom's light sources for laser interferometers used for distance measurements (laser ranging interferometer – LRI). With these powerful lasers the measuring accuracy shall be improved from several micrometers to the double-digit nanometer range. FBH laser modules can proof their capability in several satellite missions including the Grace follow-on mission 2012 aiming at precise spatially resolved measurements of the Earth's gravitational field in low earth orbit. As a result, more accurate conclusions on climate change can be drawn by determining, for example, the ice mass of Antarctica and the water stored within the continents more precisely.

< Take-off of the Earth observation satellite Sentinel – with devices from the FBH.
Raktenstart des Erdbeobachtungssatelliten Sentinel – mit Bauteilen aus dem FBH.

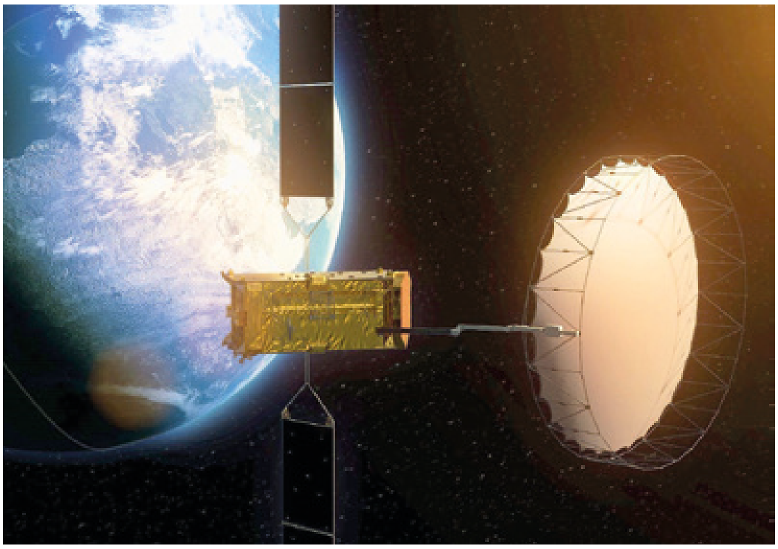
In the ongoing RaDiSat project that addresses low-noise efficient diode laser pump sources for optical transmitters in satellite communications these laser diode benches will be further developed with respect to their characteristics as pump sources. They shall improve the stability of the transmitting lasers within the satellite's LCTs in order to optimize them for future, even more challenging applications. To achieve this, the FBH relies on chip developments offering a special beam characteristic for either external reflection gratings or gratings directly implemented into the chip itself. Both variations aim at light sources delivering pump light with narrow spectral width and very low noise over a large operating space and designed for the approximately 15 years lifetime of a satellite.

Microwaves and power electronics devices for space

When the European communications satellite Alphasat I-XL took off from the spaceport Kourou in July 2013, FBH gallium nitride transistors along with several of the institute's laser diode benches for communication terminals were aboard. They are, at the same time, the first European GaN transistors ever utilized in space in a satellite experiment. These and further devices and components from microwaves and power electronics add to the comprehensive FBH competencies in diode lasers for challenging space applications.

High-efficiency GaN transceivers for satellite communications using Ka band

The most recent of FBH projects aiming at space applications was launched in autumn 2013. The European GaNSat project deals with GaN-based satellite transceivers providing high output powers and low-noise signal amplification on various frequencies of the K and Ka band for steerable phased array satellite antennas. GaNSat combines basic advancements in GaN technology with high-efficiency power amplifier designs for actively steerable antenna arrays. Due to this approach, the seven European project partners expect to achieve a technological leap for novel satellite applications. Because of the high power density of GaN devices, the overall system will be very compact. In addition, the antenna characteristics shall be steerable very precisely by combining many amplifiers. In case of a nature catastrophe, for example, an efficient communication system based on several micro-satellites could be established very quickly by steering, transmitting, and receiving beams to the affected area.



∧ Geostationary alphasat satellite with FBH GaN transistors aboard.
Geostationärer Alphasat mit GaN-Transistoren des FBH an Bord.

In cooperation with the project partners, the FBH will develop the related GaN circuits, efficient high-power amplifiers, and amplifiers with low phase-noise with respect subsequent space qualification of this GaN technology. Ka band transistors with extremely short gates and adapted epitaxial layers have already been realized at the institute. The related technological key components are just about to be integrated into the overall MMIC process at FBH.

GaN-based isolators for solid-state power amplifiers
In autumn 2013, the ESA-funded project that also aimed at satellite transceivers, more precisely at solid-state power amplifiers (SSPA), was terminated successfully. These SSPAs must be protected against reflections at the output to avoid damage of the amplifier. Conventional isolators – the usual protection of power amplifiers – are comparably bulky and thus limit further integration and miniaturization. As a result, GaN-based protective switches are an attractive option. They are particularly robust and can be operated at high temperatures. Nevertheless, they need to be protected against reflections, and accordingly diverse options have been tested within the project. Finally, in cooperation with the Dutch Organization for Applied Scientific Research (TNO) a topology was chosen that measures the actual reflection and links it to an adjustable amplification of the driver stage. With this demonstrator, a first step towards self-protecting power modules has been accomplished. In the future, such a protection mechanism could possibly be integrated within a single GaN power amplifier module or even a single GaN chip. Within this project managed by TNO the FBH develops the related GaN technology of the integrated circuits. This technology has already been successfully tested with a 2-stage power amplifier in various stress tests – without damages and degradations.

Power transistors with high linearity and efficiency
The linearity of AlGaNGaN heterojunction field-effect transistors is one of the key characteristics for modern high-bitrate communication systems. Power devices that are optimized in this respect are highly attractive for both, terrestrial and space-borne communication systems. The ESA-funded project "Linearity Assessment of GaN Technology", which was also terminated at the end of the year, had this issue in focus.

The FBH examined technologies systematically enhancing linearity and energy efficiency of GaN power transistors. To achieve this goal, epitaxy, process technology, and transistor layout have been carefully optimized in this regard. Results revealed that the linearity, among others, strongly depends on the design of the epitaxial layers. The best combination of linearity, efficiency, and output power has been achieved from power bars with an AlGaN potential barrier in the buffer layer. Accordingly, these bars have been used to establish a demonstrator amplifier used by the project partners. With them, a saturation power level of 33 watt with 66% efficiency (PAE) and a linearity (IMD3) of 15 dB could be achieved in load-pull tests. At only 2.5 dB back-off an internationally competitive IMD3 value of 25 dB can be obtained.

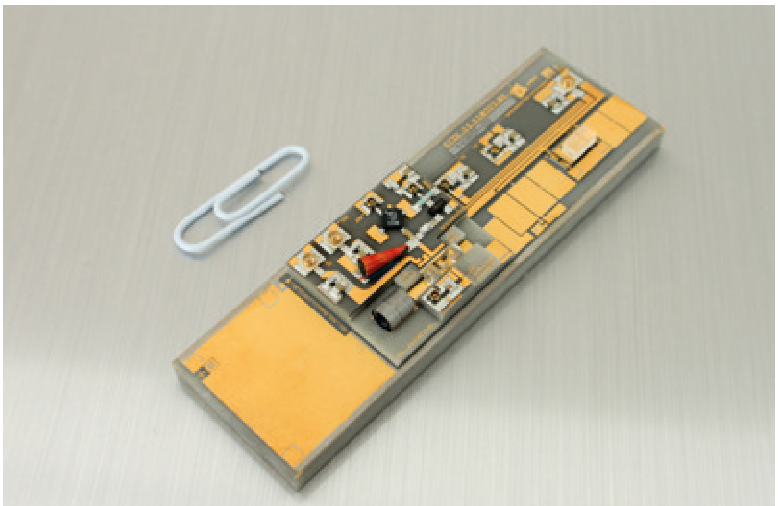
Smooth landing – imaging and target tracking with millimeter-wave radar
Landing and docking in space require imaging and target tracking sensors that work independently from illumination conditions and provide, at the same time, high spatial resolution with minimum data rates. Radar sensors at millimeter waves and with real-time image processing can fulfill these requirements. However, such sensors have not been used in space up to now. Therefore, a first-time feasibility study for a 3D imaging

system with real-time image processing and a target tracking radar has been carried out within the DLR-funded mmRadar4Space project. Investigations started in 2011 and were successfully completed in 2013. The FBH has developed the appropriate MMIC components for these radar systems based on the established in-house InP-HBT process in transfer-substrate technology. Power amplifiers in the frequency range from 70 to 100 GHz with output powers of just under 20 dBm have been demonstrated.

Satellitenkommunikation – reibungsloser Informationsaustausch unter erschwerten Bedingungen

Die Kommunikation zwischen Satelliten und zur Erde stellt besondere Anforderungen an die Technik: Die Bauteile müssen äußerst robust sein, damit sie Raketenstarts und die rauen Bedingungen im Weltraum überleben. Auch können Komponenten nicht einfach gewartet werden, wenn sie nicht mehr einwandfrei funktionieren. Daher spielt die Zuverlässigkeit eine entscheidende Rolle. Ihre Weltraumtauglichkeit müssen die Bauelemente in entsprechend anspruchsvollen Belastungstests unter Beweis stellen.

Das FBH verfügt über langjährige und umfassende Erfahrungen mit Weltraumanwendungen. Unter anderem kooperiert es seit mehr als 15 Jahren mit dem Unternehmen Tesat-Spacecom, Europas größtem Gerätelieferanten im Bereich der Satellitenkommunikation, und arbeitet über lange Jahre in Projekten mit der Europäischen Weltraumorganisation ESA. Sowohl in der Optoelektronik als auch im Bereich der Mikrowellentechnik und Leistungselektronik beschäftigen sich verschiedene F&E-Vorhaben mit der Satellitenkommunikation. Seit 2008 arbeitet eine neue Gruppe Lasermetrologie an der Entwicklung von Lasermodulen für weltraumgestützte Experimente. Daher sind inzwischen eine ganze Reihe von FBH-Bauelementen aus Optoelektronik, Mikrowellentechnik und Leistungselektronik weltraumzertifiziert.



ʌ Diode laser module from the FBH for experiments in space.
Diodenlaser-Modul aus dem FBH für Experimente im Weltraum.

Diodenlaser – zentrale Komponenten für die optische Kommunikation

Immer höhere Datenmengen werden weltweit transportiert. Satelliten haben einen wesentlichen Anteil daran, dass uns diese Informationen zuverlässig erreichen. Entsprechend verzeichnet auch das FBH eine stetig steigende Nachfrage nach seinen weltraumzertifizierten Laserdioden-Benches. Als Pumpquellen für hocheffiziente Festkörperlaser sorgen sie in Laserkommunikationsterminals (LCT) der Firma Tesat-Spacecom für die reibungslose Kommunikation. LCTs sind die Herzstücke bei der optischen Kommunikation mit Satelliten, die dafür sorgen, dass Signale mittels Licht über weite Strecken übertragen werden. Die Datenübertragungsrate ist dabei deutlich höher als bei Mikrowellen. Mit den LCTs der neuesten Generation soll eine Datenmenge von 1,8 Gigabit pro Sekunde – und damit alle 21 Sekunden der Inhalt einer Standard-DVD – über eine sehr große Distanz von 45.000 Kilometern transportiert werden. Damit wird die Übertragung von Datenpaketen zwischen Satelliten im erdnahen Orbit zwischen 200 und 2.000 Kilometern Höhe und denen im geostationären Orbit in rund 36.000 Kilometern Höhe möglich. Auch Anwendungen und Services im Bereich der Erdbeobachtung lassen sich erheblich verbessern.

<u>Erdbeobachtung und Abstandsmessung</u>

Die kompakten, weltraumqualifizierten Laserdioden-Benches aus dem Ferdinand-Braun-Institut werden unter anderem in den europäischen Sentinel-Erdbeobachtungs-satelliten eingesetzt. Geplant ist, in einer Art Datenautobahn im All, Informationen zwischen den Satelliten rund um die Uhr auszutauschen. Mehrere Sentinel-Satelliten umrunden die Erde hierbei mit hoher Geschwindigkeit – eine Umrundung dauert etwa eineinhalb Stunden. Dabei nehmen sie sehr viele Bilder von der Erde auf. Die gesammelten Daten sollen beim Vorbeiflug am Satelliten Alphasat an den geostationären Satelliten gesendet werden, der die Bilder dann zur Erde funkt.

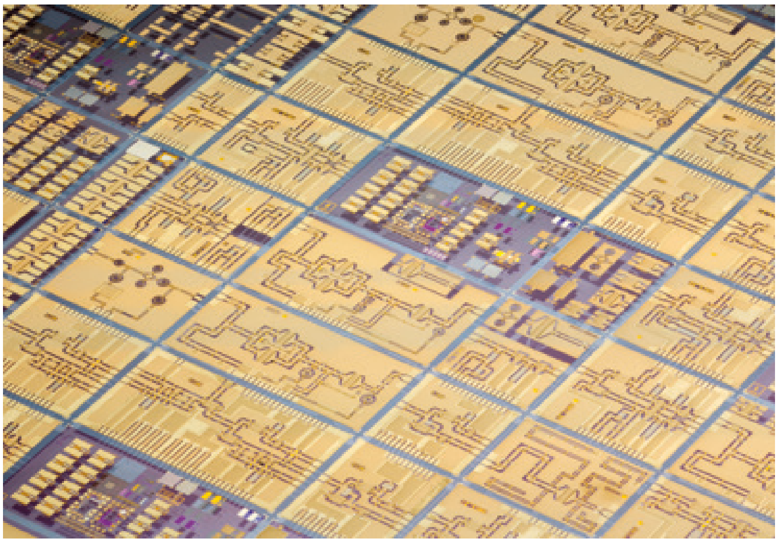
Tesat-Spacecom setzt die FBH-Laser außerdem in seinen Lichtquellen für Laser-interferometer zur Abstandsmessung (Laser Ranging Interferometer – LRI) ein. Damit soll deren Messgenauigkeit von einigen Mikrometern in den zweistelligen Nanometer-bereich verbessert werden. Die FBH-Lasermodule können dies unter anderem im Rahmen der Grace Follow-on Mission 2016 an Bord eines Satelliten zur präzisen orts-aufgelösten Vermessung des Erdgravitationsfelds im erdnahen Orbit unter Beweis stellen. Damit lassen sich exaktere Rückschlüsse auf den Klimawandel ziehen, indem beispielsweise die Eismasse der Antarktis oder das in den Kontinenten gespeicherte Wasser genauer bestimmt werden kann.

*Im laufenden Vorhaben RaDiSat – **Ra**uscharme effiziente **Di**odenlaser-Pump-quellen für optische Sender in der **Sat**ellitenkommunikation – werden diese Laser-dioden-Benches hinsichtlich ihrer Kenndaten für Pumpquellen weiterentwickelt. Sie sollen die Stabilität der Sendelaser in den LCTs der Satelliten erhöhen, um sie für künftige, noch anspruchsvollere Anwendungen zu optimieren. Das FBH setzt dabei auf Chipentwicklungen, die eine besondere Abstrahlcharakteristik für externe Reflexions-gitter ermöglichen, beziehungsweise Gitter, die in den Chip selbst integriert werden. Beide Varianten sollen Pumplicht mit geringer spektraler Breite und sehr geringem Rauschen über einen großen Arbeitsbereich für die Lebensdauer eines Satelliten von etwa 15 Jahren liefern.*

< Earth observation satellite Sentinel – also aboard are space-qualified laser diode benches from the FBH.
Erderkundungssatellit Sentinel – mit an Bord sind weltraumtaugliche Laser-dioden-Benches des FBH.

Bauelemente aus Mikrowellentechnik und Leistungselektronik für den Weltraum

Als im Juli 2013 der europäische Kommunikationssatellit Alphasat I-XL vom Weltraumbahnhof Kourou ins All startete, waren neben mehreren Laserdioden-Benches für Kommunikationsterminals auch Galliumnitrid-Transistoren des FBH mit an Bord. Das sind zugleich die ersten europäischen GaN-Transistoren, die im Weltraum in einem Satellitenexperiment eingesetzt werden. Diese und weitere Bauelemente und Komponenten aus der Mikrowellentechnik und Leistungselektronik ergänzen die umfassende Kompetenz des FBH bei Diodenlasern für anspruchsvolle Weltraumapplikationen.



∧ Monolithic-integrated GaN microwave circuits.
Monolithisch-integrierte GaN-Mikrowellenschaltkreise.

Hocheffiziente GaN-Sendeempfänger für die Satellitenkommunikation im Ka-Band

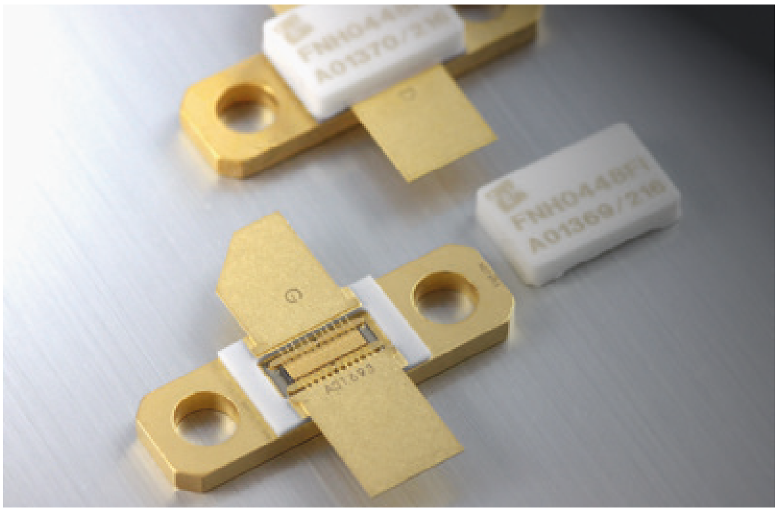
Im Herbst 2013 startete das jüngste der FBH-Vorhaben, die auf Weltraumapplikationen zielen. Das EU-Projekt GaNSat beschäftigt sich mit GaN-basierten Satelliten-Sendeempfängern. Diese sollen hohe Leistungen und rauscharme Signalverstärkung auf jeweils unterschiedlichen Frequenzen des K- und Ka-Bands für phasengesteuerte Satellitenantennen zur Verfügung stellen. GaNSat verknüpft grundlegende Weiterentwicklungen in der GaN-Technologie mit hocheffizienten Leistungsverstärker-Designs für aktiv steuerbare Antennengruppen. Durch diesen Ansatz erwarten die sieben europäischen Projektpartner einen Technologiesprung, der neue Satellitenanwendungen ermöglicht. Dank der hohen Leistungsdichte von GaN-Bauelementen wird das Gesamtsystem sehr kompakt sein. Durch die Kombination vieler Verstärker soll die Antennencharakteristik zudem gezielt steuerbar sein. So könnte beispielsweise im Katastrophenfall schnell ein effizientes Kommunikationssystem in dem betroffenen Gebiet geschaffen werden.

Das FBH wird in Kooperation mit den Projektpartnern die zugehörigen GaN-Schaltkreise, effiziente Hochleistungsverstärker und Verstärker mit geringem Phasenrauschen im Hinblick auf eine spätere Weltraumqualifizierung der GaN-Technologie entwickeln. Ka-Band-Transistoren mit extrem kurzen Gates und darauf angepassten Epitaxieschichten wurden am Institut bereits realisiert. Die zugehörigen technologischen Schlüsselkomponenten werden derzeit in den MMIC-Gesamtprozess des FBH integriert.

GaN-basierte Isolatoren für Festkörper-Leistungsverstärker

Das von der ESA geförderte Projekt, das im Herbst 2013 erfolgreich abgeschlossen wurde, zielte ebenfalls auf Satelliten-Sendempfänger (Solid-State Power Amplifier – SSPA). In diesen SSPAs müssen Festkörper-Leistungsverstärker gegen Reflektionen am Ausgang geschützt werden, da sie sonst den Verstärker schädigen. Herkömmliche Isolatoren, die Leistungsverstärker üblicherweise schützen, sind vergleichsweise groß und begrenzen damit die weitere Integration und Miniaturisierung. Daher sind GaN-basierte Schutzschalter eine attraktive Option. Sie sind besonders robust, bieten hohe Durchbruchsspannungen und können bei hohen Temperaturen betrieben werden. Da sie dennoch gegen Reflektionen geschützt werden müssen, wurden im Projekt verschiedene Varianten getestet und schließlich in Kooperation mit der niederländischen Organization for Applied Scientific Research (TNO) eine Topologie gewählt, die die tatsächliche Reflektion misst und mit einer anpassbaren Verstärkung der Treiberstufe verknüpft. Mit diesem Demonstrator wurde ein erster Schritt in Richtung eines sich selbst schützenden Leistungsmoduls entwickelt. Perspektivisch könnte ein derartiger

Schutzmechanismus in einem einzigen GaN-Leistungsverstärkermodul oder sogar in einem einzigen GaN-Chip integriert werden. Das FBH entwickelte in dem von TNO geleiteten Projekt die zugehörige GaN-Technologie der integrierten Schaltkreise. Diese wurden erfolgreich anhand eines zweistufigen Leistungsverstärkers in verschiedenen Belastungstests getestet – ohne Schäden oder Degradationen.



∧ GaN microwave power transistors for communication applications.
GaN-Mikrowellen-Leistungstransistoren für Kommunikationsanwendungen.

Leistungstransistoren mit hoher Linearität und Wirkungsgrad

Die Linearität von AlGaNGaN-Heterojunction-Feldeffekttransistoren ist eine der Schlüsseleigenschaften für moderne hochbitratige Kommunikationssysteme. Entsprechend optimierte Leistungsbauelemente sind sowohl für terrestrische wie auch für weltraumgestützte Kommunikationssysteme hochinteressant. Damit beschäftigte sich das von der ESA geförderte Projekt „Linearity Assessment of GaN Technology“, das ebenfalls Ende des Jahres erfolgreich abgeschlossen wurde.

Das FBH untersuchte Technologien, mit denen sich die Linearität und Energieeffizienz von GaN-Leistungstransistoren systematisch erhöhen lässt. Dazu wurden Epitaxie, Prozesstechnologie und Transistorlayout gezielt optimiert. Die Ergebnisse zeigten, dass die Linearität unter anderem sehr stark vom Design der Epitaxieschichten abhängt. Die beste Kombination aus Linearität, Wirkungsgrad und Ausgangsleistung wurde bei Powerbars mit einer AlGaN-Potenzialbarriere in der Bufferschicht erzielt. Diese wurden letztlich auch für den Aufbau eines Demonstratorverstärkers von den Projektpartnern genutzt. Load-Pull-Tests erreichten eine Sättigungsleistung von 33 Watt mit 66% Effizienz bei einer Linearität (IMD3) von 15 dB. Bei lediglich 2,5 dB Backoff erreicht man bereits einen international konkurrenzfähigen IMD3-Wert von 25 dB.

Besser landen: Bildgebung und Zielverfolgung mit Millimeter-Wellen-Radar

Landung und Andockung im Weltraum benötigen bildgebende und zielverfolgende Sensoren, die unabhängig von der Beleuchtungssituation bei gleichzeitig guter räumlicher Auflösung sowie minimalen Datenraten arbeiten können. Radarsensoren bei Millimeterwellen und Echtzeit-Bildverarbeitung können diese Anforderungen erfüllen. Derartige Sensoren wurden allerdings bislang noch nicht im Weltraum eingesetzt.
Im Rahmen des vom DLR finanzierten Projektes mmRadar4Space wurde von 2011 bis 2013 erstmalig eine Machbarkeitsuntersuchung für ein 3D-Bildgebungssystem mit Echtzeit-Bildverarbeitung sowie ein Zielverfolgungsradar durchgeführt. Das FBH entwickelte die zugehörigen MMIC-Komponenten für diese Radarsysteme. Basis dafür war der am Institut etablierte InP-HBT-Prozess in Transfer-Substrat-Technologie. Leistungsverstärker im Frequenzbereich von 70 bis 100 GHz mit Ausgangsleistungen von knapp 20 dBm wurden demonstriert.

Successful funding – competitive process of the Leibniz Association

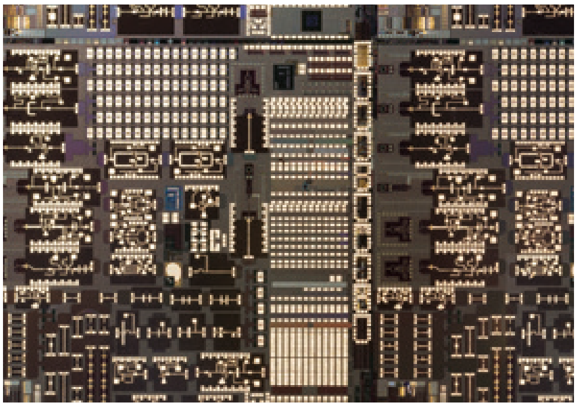
In 2013, two research proposals of the FBH scored in the yearly Leibniz Competition. The Laser Metrology group succeeded with their project "Timing the future: micro-integrated lasers for next generation portable optical clocks". Now, scientists from the FBH jointly with colleagues from Humboldt-Universität zu Berlin and Physikalisch-Technische Bundesanstalt are conducting research to develop the first European portable optical atomic clock. Such clocks occupy entire laboratories and are thus limited in their usability. As quantum sensors for gravitation they are useful for exact measurements of the Earth. Since the GPS does only function properly close to the Blue Planet, they are also required for navigation in space.

In the second successfully funded project SciFab, the Leibniz institutes IHP and FBH develop a joint technology platform. This platform combines IHP's silicon-BiCMOS technology with FBH's InP-HBT transfer substrate technology by heterointegrating both on wafer level – a unique constellation in Europe. SciFab offers external research and industrial partners a cross-institutional process line and thus a step ahead in semiconductor prototyping. Innovative terahertz applications that require higher power levels, for example, can be opened up by means of this heterointegration process.

Erfolgreich eingeworben – Wettbewerbsverfahren der Leibniz-Gemeinschaft

Im Leibniz-Wettbewerb waren 2013 zwei Anträge des FBH erfolgreich. Die Gruppe Lasermetrologie konnte sich mit ihrem Vorhaben „Timing the future: micro-integrated lasers for next generation portable optical clocks" durchsetzen. Gemeinsam mit der Humboldt-Universität zu Berlin und der Physikalisch-Technischen Bundesanstalt forschen die FBH-Wissenschaftler nun an der europaweit ersten portablen optischen Atomuhr. Derartige Atomuhren füllen bislang ganze Labore und sind daher nur begrenzt einsetzbar. Als Quantensensoren für Gravitation sind sie nützlich bei der exakten Vermessung der Erde. Auch zur Navigation im Weltraum werden sie gebraucht, da GPS nur nahe dem Blauen Planeten funktioniert.

Im zweiten geförderten Vorhaben SciFab soll eine gemeinsame Technologieplattform der Leibniz-Institute IHP und FBH entwickelt werden. Diese verbindet die Silizium-BiCMOS-Technologie (IHP) mit der InP-HBT-Transfersubstrat-Technologie (FBH) durch eine Heterointegration auf Waferebene, eine europaweit einzigartige Konstellation. Externe Forschungs- und Industriepartner sollen durch SciFab auf eine institutsübergreifende Fertigungslinie zuzugreifen können, was eine neue Qualität im Halbleiter-Prototyping bedeutet. Mittels dieser Heterointegration lassen sich unter anderem innovative Terahertz-Anwendungen erschließen, die höhere Leistungspegel benötigen.



∧ These chips combine the best of both technology worlds – high complexity SiGe-BiCMOS with high-power InP technology.
Diese Chips kombinieren die Vorteile von zwei Technologie-Welten: hochkomplexe SiGe-BiCMOS mit Hochleistungs-InP-Technologie.

Expansion – more space for a growing institute

On September 25, the FBH laid the foundation stone for an extension building. Thus, 1,800 square meters additional laboratory and office space shall be available as of 2015. Before, a new building had been erected in 2005, offering a supplementary area of 1,200 square meters. This demand arises from a constantly growing amount of projects that are executed by an increasing number of employees. Accordingly, FBH staff almost doubled within the last ten years.

Ausbau – mehr Platz für ein wachsendes Institut

Am 25. September hat das FBH den Grundstein für einen Erweiterungsbau gelegt – ab 2015 sollen damit 1.800 Quadratmeter Labor- und Büroräume zusätzlich zur Verfügung stehen. Bereits im Jahr 2005 waren mit der Fertigstellung eines Neubaus 1.200 Quadratmeter Fläche hinzugekommen. Hintergrund ist die stetig steigende Zahl von Projekten, die von einer wachsenden Anzahl von Mitarbeiterinnen und Mitarbeitern bearbeitet werden. Die FBH-Belegschaft hat sich in den letzten zehn Jahren beinahe verdoppelt.

∧ Laying of the foundation stone (f.l.t.r.): G. Tränkle (FBH), J. Matzke (architect), J. Koch-Unterseher (Berlin senate), M. Urban (FVB).
Grundsteinlegung für den Erweiterungsbau: (v.l.n.r.): G. Tränkle (FBH), J. Matzke (Architekt), J. Koch-Unterseher (Senatsverwaltung Berlin), M. Urban (FVB).

Try out research

∧ Hands-on-experiments at the Girls' Technology Congress.
Praktische Experimente beim Mädchen-Technik-Kongress.

Kick-off for "Schülerforschungszentrum" Berlin
On August 14, the newly founded "Schülerforschungszentrum" (student research center) at Lise-Meitner-Schule was introduced. Among the partners are the FBH, Technische Universität Berlin, and Berlin Chemie. Students of all ages can carry out experiments under professional supervision and work on own research issues, for example, related to the "Jugend forscht" (youth researches) and "Jugend testet" (youth tests) competitions. The multifaceted open offers aim to attract more teenagers to opt for a career in MINT (**m**athematics – **i**nformatics – **n**atural sciences – **t**echnology). Due to the close connection with institutions and companies carrying out research, students shall gain insight-views into everyday working life and thus professional orientation at an early stage.

Girls' Technology Congress in Adlershof
For the fourth time already, the Science Management Department and ZEMI, the Center for Microsystems Technology Berlin, organized the regional Girls' Technology Congress – this time in close proximity to the FBH in Adlershof. 140 girls from Berlin and Brandenburg of grade 7 and higher took the workshops offered as a chance to experience what it feels like to work in a technically oriented profession. They were milling metal, soldering electrical circuits, constructing their own bridges, and even programming robots and formula 1 race cars. Aim of the congress is to arouse interest of girls for MINT occupations in general and to help overcoming preconceptions and anxieties regarding engineering and natural-scientific professions amongst girls. With activities like these, skilled personnel shall be sustainably secured for industry and research institutions. Next year, the event is going to become international with workshops offered in English language for the first time.

Forschung ausprobieren

Schülerforschungszentrum Berlin gestartet
*Am 14. August eröffnete das neu gegründete Schülerforschungszentrum an der Lise-Meitner-Schule. Partner sind unter anderem das FBH, die Technische Universität Berlin und Berlin Chemie. Schülerinnen und Schüler aller Altersstufen können dort unter fachkundiger Anleitung experimentieren und eigene Fragen – etwa für die Wettbewerbe „Jugend forscht" und „Jugend testet" – bearbeiten. Die vielfältigen, offenen Angebote sollen mehr Jugendliche für MINT-Berufe (**M**athematik, **I**nformatik, **N**aturwissenschaften und **T**echnik) begeistern. Durch die enge Anbindung an forschende Institute und Unternehmen sollen die Schülerinnen und Schüler auch Einblicke in die Berufswelt und dadurch schon frühzeitig eine berufliche Orientierung erhalten.*

Mädchen-Technik-Kongress in Adlershof
Bereits zum vierten Mal organisierten die Abteilung Wissenschaftsmanagement und das Zentrum für Mikrosystemtechnik Berlin (ZEMI) den regionalen Mädchen-Technik-Kongress, der dieses Mal in Adlershof stattfand. 140 Mädchen aus Berlin und Brandenburg ab der siebten Jahrgangsstufe hatten die Möglichkeit, in Workshops auszuprobieren, wie sich ein technischer Beruf anfühlt. Sie frästen Metall, löteten elektronische Schaltungen, konstruierten eigene Brücken oder programmierten sogar Roboter und Formel-1-Wagen. Ziel ist es, Mädchen für MINT-Berufe zu begeistern und Berührungsängste und Vorurteile gegenüber ingenieur- und naturwissenschaftlichen Berufen bei Mädchen abzubauen. Damit sollen auch Fachkräfte für die Wirtschaft und Forschung nachhaltig gesichert werden. Das Angebot soll beim nächsten Mal internationaler werden; erstmals werden dann Workshops auch in Englisch angeboten.

Integrated management system – again successfully certified

The three internationally approved certificates for quality, environmental management, and occupational health and safety have been renewed for another year. No deviations from the corresponding standards (ISO 9001, 14001, 18001) could be observed. Among others, the auditors positively emphasized the dedicated involvement of FBH staff and the preeminent expertise of qualified employees in the areas audited. As laws are becoming stricter, the auditors suggested to integrate the regulations associated with the increasingly complex technical infrastructure at the FBH into the processes of the integrated management system in the future.

GL ISO 9001 ISO 14001 OHSAS 18001
GL Systems Certification

Integriertes Managementsystem – erneut erfolgreich zertifiziert

Die drei international gültigen Zertifikate für die Bereiche Qualität, Umwelt und Arbeitssicherheit wurden beim jährlichen Audit wieder für ein Jahr verlängert. Es gab keine Abweichungen von den entsprechenden Normen (ISO 9001, 14001, 18001). Besonders positiv hervorgehoben wurden von den Auditoren unter anderem das Engagement der Mitarbeiterinnen und Mitarbeiter und die sehr guten fachlichen Kenntnisse der Fachkräfte in den auditierten Bereichen. Angeregt wurde, die sich verschärfenden Gesetzesvorgaben im Zusammenhang mit einem immer komplexeren Maschinenpark am FBH künftig stärker in die Abläufe des Managementsystems zu integrieren.

Fairs & events

Organized by FBH for the expert audience

WOCSDICE 2013

Current development trends in semiconductor devices were the main topic of the 37. WOCSDICE (Workshop on Compound Semiconductor Devices and Integrated Circuits). The conference, organized by the Ferdinand-Braun-Institut, was held in Warnemünde, Germany, from May 26 - 29 and attracted more than 85 participants from all over the world. The main focus was on GaN-based developments for power electronics, revealing the great potential of this technology for future energy-efficient power converters. Further highlights were the sessions on THz technology and developments integrating compound semiconductors on silicon as active circuit components into highly integrated semiconductor generations.

< Participants of the 37. WOCSDICE in Warnemünde.
Teilnehmer der 37. WOCSDICE in Warnemünde.

WideBaSe conference

The results gained from three years of collaboration within the regional growth core Berlin WideBaSe were presented in September by the 13 partners at their 2-day conference on technology and applications of nitride semiconductors in Berlin. Berlin WideBaSe stands for research, development and commercialization of optoelectronic and electronic devices based on **wide-ba**ndgap **se**miconductors. The wide bandgap of 3rd and 5th group compound semiconductors results in special properties as, for example, especially high thermal conductivity and operability even at high temperatures. If one can cope with the challenging process steps, from the material to the device to the final product, entirely new applications can be opened up. Berlin WideBaSe, managed by the Ferdinand-Braun-Institut, yielded not only high-level scientific output, but also many novel starting points for bilateral cooperation. The close collaboration also laid the foundation for the success of "Advanced UV for Life" in the BMBF competition Zwanzig20 – with many of the WideBaSe partners aboard.

Expert exchange at conferences & trade fairs
In 2013, the FBH once more presented the institute to the specialist audience by talks, poster presentations, workshops, and trade fair exhibitions. In the microwaves field, the European Microwave Week was a particular highlight to mention. The FBH did not only show latest research results, Wolfgang Heinrich also acted as chair and co-chair of various sessions at the largest European microwaves, RF, wireless and radar event.

In the optoelectronics field, three important conferences and fairs were held in 2013: Photonics West in San Francisco (USA) in February, Laser World of Photonics in Munich three months later, and CLEO 2013 in San Jose (USA) in June. At Photonics West, the world's largest annual semiconductor laser and photonics meeting, the FBH expanded its presence with nine talks and further contributions as co-authors. In addition, Michael Kneissl and Paul Crump were holding two sessions as chairs. At the biggest European laser fair Laser World of Photonics, the FBH introduced miniaturized laser sources and diode lasers for the red spectral region using a novel grating technology for wavelength selection. And at CLEO 2013 (Conference on Lasers and Electro Optics), the CryoLaser project has been spotlighted as "hot topic", thus Paul Crump presented the FBH project at a special press luncheon. The goal of CryoLaser is to develop a novel diode laser technology required for the deployment of laser-induced fusion systems. Such systems shall be used as clean, safe, high-efficiency power source, as well as an instrument for basic research.

FBH for the general public – Girls' Day & Science Night
In April, the FBH – like in recent years – offered a special program for the Girls' Day event. Trainees and young scientists showed 20 girls their working environment and shared their expertise related to FBH's tiny, powerful lasers. When peering through the microscope and piling up laser stacks, a steady hand and a delicate touch was needed.

For the interested public, the Science Night was an additional chance to learn more about the FBH and its research. Around 730 visitors took the opportunity to participate in cleanroom and laboratory tours as well as to execute practical experiments.

FBH internally – children party 2013
On June 13, the children party for the offspring of FBH's employees took place already for the fourth time. Every two years the organizing team sets up an entertaining program, with the inflatable jumper, bobby car races, and face painting for the youngest – goal wall shooting, basketball, and tug of war games is offered for the older children. Also, food for the brain is provided, since everybody who wants to has the opportunity to visit the epitaxy cleanroom.

^ The institute's offspring at the 4th FBH children party.
Der Instituts-Nachwuchs beim 4. FBH-Kinderfest.

Messen & Veranstaltungen

Vom FBH für die Fachwelt organisiert

WOCSDICE 2013
Aktuelle Entwicklungstrends bei Bauelementen auf Basis von Verbindungshalbleitern standen im Fokus der 37. WOCSDICE (Workshop on Compound Semiconductor Devices and Integrated Circuits). Die vom Ferdinand-Braun-Institut organisierte Konferenz fand vom 26.-29. Mai 2013 in Warnemünde statt. Mehr als 85 Teilnehmende aus aller Welt besuchten das breit gefächerte Vortragsprogramm. Der Schwerpunkt

lag auf Entwicklungen aus der GaN-Leistungselektronik, die das große Potenzial der Technologie für künftige energieeffiziente Leistungswandler zeigten. Sessions zur THz-Technologie sowie zu den Möglichkeiten, Verbindungshalbleiter auf Silizium als aktive Schaltelemente in hochintegrierten Halbleitergenerationen einzusetzen, ergänzten das Programm.

WideBaSe-Konferenz
*Die Ergebnisse aus drei Jahren Zusammenarbeit im regionalen Wachstumskern Berlin WideBaSe präsentierten die insgesamt 13 Partner im September in Berlin bei ihrer zweiten Tagung zu Technologie und Anwendungen von Nitrid-Halbleitern. Berlin WideBaSe steht für Forschung, Entwicklung und Vertrieb von optoelektronischen und elektronischen Bauelementen auf Basis von breitlückigen Halbleitern. Aus der großen Bandlücke von Verbindungshalbleitern der 3. und 5. Hauptgruppe des Periodensystems (**Wide-Ba**ndgap-**Se**miconductors) resultieren spezielle Eigenschaften, beispielsweise eine besonders gute Wärmeleitfähigkeit und Funktionsfähigkeit auch bei hohen Temperaturen. Beherrscht man die anspruchsvollen Prozessschritte, vom Material über das einzelne Bauelement bis hin zum fertigen Produkt, eröffnen sich vollkommen neue Anwendungen. Unter Federführung des Ferdinand-Braun-Instituts sind in diesem Rahmen neben dem wissenschaftlichen Output viele neue bilaterale Anknüpfungspunkte entstanden. Die enge Zusammenarbeit legte auch den Grundstein für den Erfolg mit „Advanced UV for Life" im BMBF-Wettbewerb Zwanzig20, bei dem viele der WideBaSe-Partner mit an Bord sind.*

Expertenaustausch auf Konferenzen & Messen
Auch 2013 präsentierte sich das FBH der Fachwelt wieder auf zahlreichen Veranstaltungen durch Vorträge, Posterpräsentationen, Workshops und Messeauftritte. Im Bereich der Mikrowellentechnik ist besonders die European Microwave Week hervorzuheben. Auf dem größten europäischen Mikrowellen-, RF-, Wireless- und Radar-Event zeigte das FBH nicht nur aktuelle Forschungsergebnisse, Wolfgang Heinrich leitete darüber hinaus verschiedene Sessions als Chair beziehungsweise Co-Chair.

Im Bereich der Optoelektronik fanden 2013 gleich drei wichtige Konferenzen und Messen statt: die Photonics West in San Francisco (USA) im Februar, die Laser World of Photonics in München drei Monate später und die CLEO 2013 in San Jose (USA) im Juni. Auf der Photonics West, der weltgrößten, jährlich stattfindenden Messe und Konferenz in Bereich der Halbleiterlasertechnik, baute das FBH seine Präsenz mit neun Vorträgen und weiteren Beiträgen als Mitautoren aus. Michael Kneissl und Paul Crump waren zudem Chairs zweier Sessions. Auf der größten europäischen Laserfachmesse Laser World of Photonics stellte das FBH miniaturisierte Laserstrahlquellen sowie Diodenlaser für den roten Spektralbereich vor, die eine neuartige Gittertechnologie zur Wellenlängenselektion nutzen. Und auf der CLEO 2013 (Conference on Lasers and Electro Optics) wurde das FBH-Projekt CryoLaser zum „hot topic" gekürt und auf einem speziellen Presseevent von Paul Crump präsentiert. CryoLaser zielt auf die Entwicklung einer neuartigen Diodenlasertechnologie, mit der sich laserinduzierte Fusionssysteme realisieren lassen. Diese sollen künftig als saubere, sichere und hocheffiziente Energiequellen sowie als Werkzeuge für die Grundlagenforschung dienen.

^ Paul Crump presenting FBH's CryoLaser project as "hot topic" at the CLEO fair.
Paul Crump präsentiert das CryoLaser-Projekt des FBH als „hot topic" auf der Fachmesse CLEO.

∧ Highlight of the FBH's Science Night program – children's cleanroom tour.
Highlight des FBH-Programms zur Langen Nacht der Wissen-schaften: Kinderführung im Reinraum.

FBH für die Öffentlichkeit: Girls' Day & Lange Nacht der Wissenschaften

Im April lud das FBH wie in jedem Jahr 20 Schülerinnen zum Girls' Day ein. Auszubildende und Nachwuchswissenschaftlerinnen und -wissenschaftler zeigten ihre Arbeitsumgebung und vermittelten viel Wissenswertes rund um die winzigen, leistungsstarken FBH-Laser. Beim Blick durchs Mikroskop und beim Stapeln von Laserstacks waren eine ruhige Hand und viel Fingerspitzengefühl gefragt.

Auch die Lange Nacht der Wissenschaften bot der interessierten Öffentlichkeit die Chance, mehr über das FBH und seine Forschung zu erfahren. Etwa 730 Besucherinnen und Besucher nutzten 2013 die Möglichkeit zu Reinraum- und Laborführungen sowie praktischen Experimenten.

FBH intern: Kinderfest 2013

Am 13. Juni fand bereits das vierte Kinderfest am Ferdinand-Braun-Institut für die Kinder der Mitarbeiterinnen und Mitarbeiter statt. Alle zwei Jahre stellen die Organisatoren ein buntes Programm auf die Beine: Hüpfburg, Bobby-Car-Rennen und Kinderschminken für die Kleinen – Torwandschießen, Basketball und Tauziehen für die Größeren. Geistiges Futter gab es natürlich auch: wer wollte, durfte den Epitaxie-Reinraum besichtigen.

Awards & personal particulars

Günther Tränkle takes charge of IKZ on a temporary basis

Since October 1, the Director of the Ferdinand-Braun-Institut additionally took over a one-year interim responsibility for the Leibniz Institute for Crystal Growth (IKZ). Both institutes belong to the Forschungsverbund Berlin e.V. The position became vacant since Roberto Fornari followed a call of the University Parma on a professorship at the end of September. He has been Director of the IKZ for ten years.

Günther Tränkle re-confirmed as OpTecBB Chairman

At the meeting of members of the Competence Network for Optical Technologies Optec-Berlin-Brandenburg (OpTecBB) in September, a new executive board has been elected. Already for the fourth time, Günther Tränkle from the Ferdinand-Braun-Institut has been re-confirmed as chairman; new in the board are Peter Krause, Martin Schell, Adrian Mahlkow, and Gerrit Rössler.

Award-winning publications

DOPS Prize for PhD achievements

In November 2013, the Danish Optical Society (DOPS) has awarded André Müller with the DOPS Prize for his achievements in his PhD, which he has completed at Technical University of Denmark. André Müller has been working with the FBH before his thesis and afterwards returned to FBH. According to the jury, "He has developed a number of state-of-the-art, high-power and high-brightness lasers systems in the infrared region and in the visible green region. Among these laser systems, two laser systems have been considered as so outstanding that the Danish Optical Society determined that André Müller should be given the DOPS Prize."

Best Paper Award EMC
Eberhard Richter has been awarded with the Best Paper Award at Electronic Materials Conference (EMC 2013) for the paper "Si-doping of GaN in HVPE" published by E. Richter, T. Stoica, U. Zeimer, C. Netzel, M. Weyers, and G. Tränkle – the topic was presented at the conference one year before. The publication deals with the growth of n-doped GaN crystals using hydride vapor phase epitaxy. It also examines the strain resulting from silicon-doping of GaN.

EuMIC Prize
For the presentation of the publication "A 164 GHz Hetero-Integrated Source in InP-on-BiCMOS Technology" by T. Jensen, T. Al-Sawaf, M. Lisker, S. Glisic, M. Elkhouly, T. Krämer, I. Ostermay, C. Meliani, B. Tillack, V. Krozer, and W. Heinrich, the FBH received the EuMIC Prize 2013. The acknowledgement has been bestowed at the European Microwave Integrated Conference (EuMIC) and is endowed with 3,000 Euros. The paper summarizes the results of a joint project with the Leibniz-Institut für innovative Mikroelektronik (IHP).

Highlight publication "Semiconductor Science and Technology"
The publication "High-power, spectrally stabilized, near-diffraction-limited 970 nm laser light source based on truncated-tapered semiconductor optical amplifiers with low confinement factors" by X. Wang, G. Erbert, H. Wenzel, B. Eppich, P. Crump, A. Ginolas, J. Fricke, F. Bugge, M. Spreemann, and G. Tränkle has been selected as highlight publication by the editors of the "Semiconductor Science and Technology" journal. The criteria referred to outstanding research results and their impact on the semiconductor community.

Highlight publication "Plasma Sources Science and Technology"
The publication of H. Porteanu, R. Gesche, and K. Wandel, which has been published in "Plasma Sources Science and Technology" in 2013, has been selected by the editors of the journal as highlight 2013. According to the jury, "Highlights are selected based on outstanding research and impact on the low-temperature plasmas community, for which your article is highly regarded".

Auszeichnungen & Personalia

Günther Tränkle übernimmt kommissarische Leitung des IKZ
Der Direktor des Ferdinand-Braun-Instituts hat zum 1. Oktober für ein Jahr kommissarisch die Leitung des Leibniz-Instituts für Kristallzüchtung (IKZ) mit übernommen. Beide Institute gehören zum Forschungsverbund Berlin e.V. Die Stelle war vakant geworden, nachdem Roberto Fornari Ende September nach zehnjähriger Direktorentätigkeit am IKZ dem Ruf auf eine Professur an die Universität Parma gefolgt war.

Günther Tränkle erneut als OpTecBB-Vorstandsvorsitzender bestätigt
Auf der Mitgliederversammlung des Kompetenznetzes Optische Technologien Berlin-Brandenburg OpTecBB e.V. wurde im September ein neuer Vorstand gewählt. Vorstandsvorsitzender wurde bereits zum vierten Mal Günther Tränkle vom Ferdinand-Braun-Institut; neu im Vorstand sind Peter Krause, Martin Schell, Adrian Mahlkow und Gerrit Rössler.

∧ Award ceremony of the DOPS prize (l. L. Lindvold, r. André Müller).
Preisverleihung des DOPS-Preises (l. L. Lindvold, r. André Müller).

Preisgekrönte Publikationen

DOPS-Preis für herausragende Dissertation
Im Januar 2014 überreichte Lars Lindvold von der Dänischen Optischen Gesellschaft (DOPS) André Müller den DOPS-Preis 2013 für seine Dissertation. André Müller hat vor seiner Dissertation an der Dänischen Technischen Universität (DTU) am FBH gearbeitet und kehrte anschließend wieder dorthin zurück. In der Arbeit beschäftigte er sich mit neuen Lasersystemen mit hoher Leistung und Brillanz im nah-infraroten und grünen Spektralbereich. Darunter waren zwei so herausragende Lasersysteme, dass die Jury der Dänischen Optischen Gesellschaft ihm den DOPS-Preis zuerkannte.

Best Paper Award EMC
Für das Paper von E. Richter, T. Stoica, U. Zeimer, C. Netzel, M. Weyers und G. Tränkle „Si-doping of GaN in HVPE" wurde Eberhard Richter auf der Electronic Materials Conference (EMC 2013) mit dem Best Paper Award ausgezeichnet – das Thema war auf der Konferenz im Jahr zuvor präsentiert worden. Die Veröffentlichung beschäftigt sich mit dem Wachstum von n-dotierten GaN-Kristallen mittels Hydridgasphasenepitaxie und untersucht die bei Silizium-Dotierung von GaN beobachteten Verspannungen.

EuMIC-Preis
Für die Präsentation der Publikation von T. Jensen, T. Al-Sawaf, M. Lisker, S. Glisic, M. Elkhouly, T. Krämer, I. Ostermay, C. Meliani, B. Tillack, V. Krozer und W. Heinrich „A 164 GHz Hetero-Integrated Source in InP-on-BiCMOS Technology" erhielt das FBH den EuMIC-Preis 2013. Dieser wurde auf der European Microwave Integrated Conference (EuMIC) verliehen und ist mit 3.000 Euro dotiert. Das Paper fasst die Ergebnisse eines Projektes mit dem Leibniz-Institut für innovative Mikroelektronik (IHP) zusammen.

Highlight-Publikation bei „Semiconductor Science and Technology"
Die Veröffentlichung von X. Wang, G. Erbert, H. Wenzel, B. Eppich, P. Crump, A. Ginolas, J. Fricke, F. Bugge, M. Spreemann und G. Tränkle, „High-power, spectrally stabilized, near-diffraction-limited 970 nm laser light source based on truncated-tapered semiconductor optical amplifiers with low confinement factors" wurde von der Redaktion der Zeit-schrift „Semiconductor Science and Technology" als Highlight-Publikation ausgewählt. Kriterien waren herausragende Forschungsergebnisse und deren Einfluss auf die Halbleiter-Community.

Highlight-Publikation bei „Plasma Sources Science and Technology"
Die Publikation von H. Porteanu, R. Gesche und K. Wandel, die 2013 im Journal „Plasma Sources Science and Technology" veröffentlicht wurde, wurde von der Redaktion des Journals als Highlight 2013 ausgewählt. „Highlights are selected based on outstanding research and impact on the low-temperature plasmas community, for which your article is highly regarded", so die Begründung.

Science Management
Wissenschaftsmanagement

Science Management – comprehensive services and strategic networking for thriving research and development

The Science Management Department strategically advises and supports the director as well as FBH scientists regarding industrial projects, project funding, and in establishing R&D cooperation. By positioning the institute in local, regional, national, and international networks, the department helps increasing the public visibility of the FBH. Research and industrial partners additionally benefit from these activities. The interdisciplinary team accomplishes administrative and non-scientific work related to applications for complex collaborative projects, coordination of national and international project clusters, as well as in the development and management of such projects. The systematic complaint management invented last year additionally takes off pressure from scientists as they can focus on R&D instead of handling reclamations related to purchase and delivery. This service has been implemented in mid-2013 within an internal restructuring process and helps avoiding time delays and costs. Since 2012, the central service units administration and IT support have been assigned to the Science Management Department, thus helping to bundle scientific support and information flow. These units now add to the team's established competence areas strategy, technology transfer & marketing, and education & training.

Science Management Department

Strategy	Technology Transfer & Marketing	Education & Training Management	Administration & IT Support
support of strategy development strategic cooperation networking	project management processing of R&D results projected development research cooperation application laboratories	coordination of education & training networks promotion of young scientists concepts for education & training	administration including finances, controlling, human resources, sales, ... IT support

Services for FBH:
project development & project management
search and acquisition for subsidies
development & management of cooperations
inspiring young scientific talents
professional administration & IT support

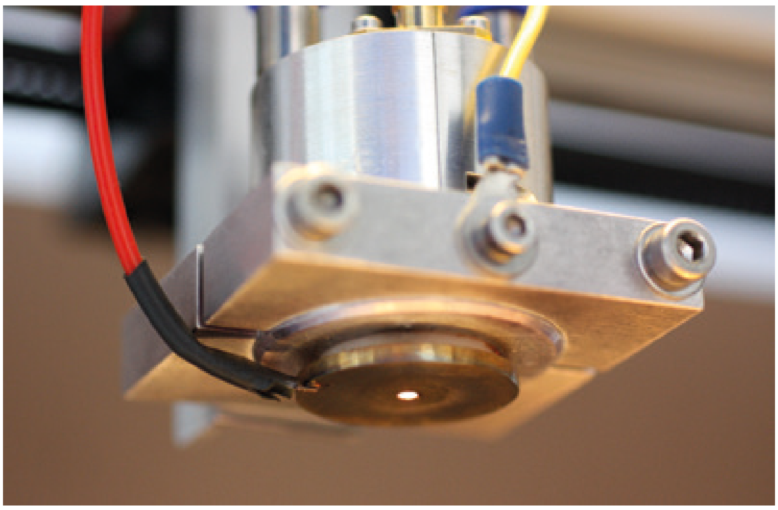
Interface between science and industry
One highlight of 2013 was the successful participation in the BMBF competition Zwanzig20, where the FBH has submitted an initial concept entitled "Advanced UV for Life" (see also highlights, p. 21). Ideas and input received from a total of 23 partners from science and industry were included and edited by the Science Management Department. This coordination implies a wide range of organizational tasks that are barely manageable for scientists in addition to their actual R&D work. By involving the Science Management team, the efforts of such a competition could be kept at a low level for the R&D departments of the institute and the participating partners. In close coordination with the Director and in collaboration with the Business Area GaN Optoelectronics and the Materials Technology Department, the concept has been developed. "Advanced UV for Life" prevailed together with nine other consortia out of overall 59 submitted initial concepts. The German-wide consortium is dedicated to research, development, and application of UV LED technology and is funded with up to 45 million Euros until 2020. The research on UV LEDs at FBH can thus be strongly supported over the next years and be further advanced to concrete applications, for example in water disinfection. This outcome is also an excellent reference for FBH's fundamental strategic approach to closely crosslink with partners from research, which additionally increases public visibility of the institute within the respective subject area. Consequently, the FBH continued its activities within the regional technology networks Berlin WideBaSe, the Center for Microsystems Technology (ZEMI), and the competence network for optical technologies OpTecBB.

Being a part of the Berlin WideBaSe network, which has been funded as a regional growth core over the last three years by the BMBF, new projects could get started at the FBH. They add to already existing projects between the network partners. Building up on this track record, all partners agreed to continue the cooperation beyond the funding period in mid-2013. A direct outcome of this successful networking is "Advanced UV for Life"; another column of activities in this field is the structured exchange with Polish institutions revolving around nitride semiconductors. This interchange between Berlin and Warsaw – both are centers of nitride semiconductor research and development in Europe – was continued in 2013 with the second "German-Polish Workshop on Nitride Semiconductors", this time in Warsaw. Moreover, 80 conference participants took the opportunity to get an update on current developments and to exchange expert information at the "2nd Berlin WideBaSe Conference on Technology and Applications of Nitride Semiconductors".

Active in technology and knowledge transfer

In the field of technology transfer, the department supported the vibrant spin-off activities of FBH colleagues. On top of that, one team member is directly involved in the spin-off BEAPLAS, helping to create the business plan and to establish business activities. The BEAPLAS GmbH develops and markets processes and equipment for thin-film coating at atmospheric pressure. Central tool is a plasma source operating at atmospheric pressure. It was developed during the last years and optimized for several different applications, ranging from automotive to medical technology. Expensive vacuum technology is widely used in this field today, thus cost-effective atmospheric tools are commercially attractive. The spin-off, founded in May 2013, is supported by the European Union and the Federal Ministry for Economic Affairs and Energy within the EXIST-Forschungstransfer program.

∧ Berlin WideBase conference in September 2013.
Berlin WideBaSe-Konferenz im September 2013.



∧ Compact microwave plasma sources like this will be further developed and marketed by BEAPLAS.
Kompakte Mikrowellen-Plasmaquellen wie diese will BEAPLAS künftig weiterentwickeln und vermarkten.

From vocational orientation to tailor-made further training – good practice & new concepts

As in the years before, the education and training group aimed at attracting young people to opt for a career in science, technology, engineering, and mathematics (STEM) in general and in microsystems technology in particular. Many training possibilities in this field are still fairly unknown or seem to be unattractive especially to girls. Apart from vocational orientation, the FBH also sets great value upon additional topics concerning education and training, especially further training and the apparent gap between existing offers and specific needs of companies as a consequence of rapid technological advancement.

In 2013, the FBH extended and intensified its cooperation with schools to inform about vocational and academic training opportunities. New partnerships were initiated based on the Berlin program for vocational orientation BvBo (Berliner Programm für vertiefte Berufsorientierung). In close cooperation with ZEMI, the Center for Microsystems Technology Berlin, and OpTecBB, the competence network for optical technologies and microsystems technology in Berlin Brandenburg, a mix of different actions was taken to spread information about career prospects. The FBH took part in several fairs and exhibitions.

One of the highlights in 2013 was the 4th Girl's Technology Congress, which is linked to the nation-wide network mstlfemNet meets Nano and Optics, funded by the Federal Ministry for Education and

< Girl programming her racing car at the 4th Girl's Technology Congress.
Ein Mädchen programmiert ihr Formel-1-Auto auf dem 4. Mädchen-Technik-Kongress.

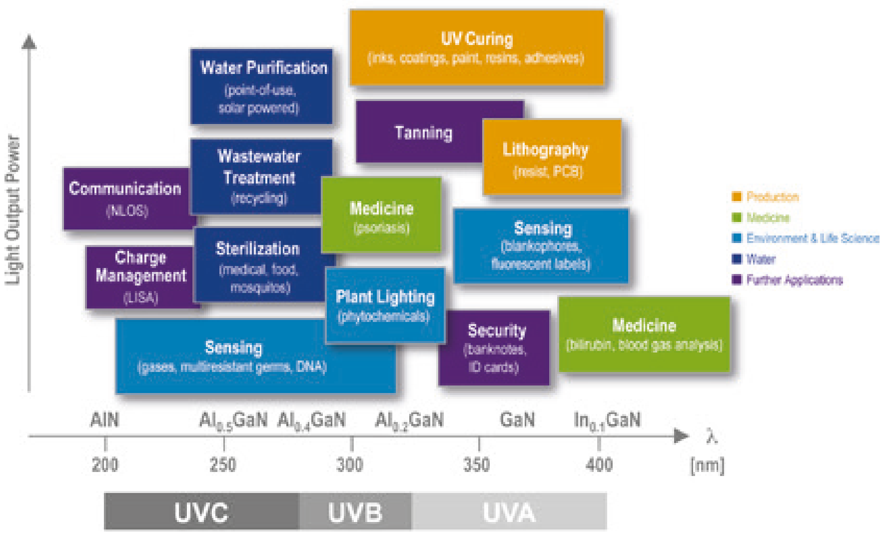
Research. This time, the one-day event was held at the Adlershof Science and Technology Park. The FBH as main organizer was supported by many local and regional protagonists offering practical workshops as well as guided tours. The participants visited companies, institutes, and historical technical sites like the wind tunnel, the sphere-shaped thermo laboratories, and the former airfield. Around 170 schoolgirls from grades 7 - 12 from the Berlin-Brandenburg region could choose from a variety of hands-on experiments combined with insights in everyday working life of technicians and scientists. An additional workshop was offered for teachers. Furthermore, the FBH initiated round tables to enlarge the network of multipliers, to raise awareness in gender matters, and to inform about jobs and training opportunities in optics and microsystems technology. First steps were taken to transfer the well-proven good practice example of the Girl's Congress to other EU countries, linking it with new ideas and experiences form partners abroad. With a special focus on photonics the new project within the 7th framework program will start in January 2014.

The 8th Microsystems Summer School and the 2nd Leibniz-Doktorandenforum Section D were also organized by the Science Management Department. These activities comprised several training offers like seminars, lectures, and visits in research institutes as well as high-tech laboratories. At the traditional "Summer School meets Company" evening, students took the chance to get in contact with representatives from institutes and companies affiliated within ZEMI. Discussion topics covered latest research findings as well as practical subjects like how to find a job or cooperation to complete bachelor and master theses.

The Science Management Department also helped providing political decision makers with demand-based information concerning training needs. On behalf of the Berlin Senate for Economy, Technology and Science, the group analyzed current needs of companies in the optics and microtechnology field. Managing directors and human resources managers from more than 20 companies and institutes were interviewed. The survey revealed that apart from traditional training courses there is a very special interest in tailor-made trainings, each for a very limited number of people. It also became obvious that by enhancing the cooperation between companies and research institutes existing resources and competencies could be utilized in a more effective and synergetic way.

Wissenschaftsmanagement – vielfältige Dienstleistungen und strategische Vernetzung für Forschung und Entwicklung

Die Abteilung berät und unterstützt die Institutsleitung sowie Wissenschaftlerinnen und Wissenschaftler am FBH strategisch bei Industrieprojekten, Fördervorhaben und beim Aufbau von F&E-Kooperationen. Sie positioniert das Institut in lokalen, regionalen, nationalen und internationalen Netzwerken und erhöht so dessen öffentliche Sichtbarkeit. Auch Forschungs- und Unternehmenspartner des FBH profitieren von diesen Aktivitäten. Das interdisziplinär aufgestellte Team übernimmt administrative und nicht-wissenschaftliche Arbeiten, die bei der Beantragung komplexer Verbundvorhaben, der Koordination nationaler und internationaler Projektverbünde oder bei der Entwicklung und dem Management solcher Vorhaben anfallen. Mit dem im letzten Jahr eingeführten Reklamationsmanagement entlastet das Team zudem die wissenschaftlich arbeitenden Kolleginnen und Kollegen. Ziel ist es, Zeitverzögerungen und Kosten, die durch Probleme bei Beschaffung und Lieferung entstehen, zu minimieren. Dieser Service wurde im Rahmen der Integration der Serviceeinheiten Verwaltung und EDV Mitte letzten Jahres in das Wissenschaftsmanagement eingeführt. Seit 2012 ergänzen diese beiden Bereiche die bisherigen Kompetenzfelder Strategie, Technologietransfer und Marketing sowie Bildungsmanagement.



∧ Application fields of the "Advanced UV for Life" consortium.
Anwendungsfelder des Konsortiums „Advanced UV for Life".

Schnittstelle zwischen Wissenschaft und Wirtschaft

Ein Highlight 2013 war die erfolgreiche Teilnahme am BMBF-Wettbewerb Zwanzig20, bei dem das FBH ein Initialkonzept mit dem Titel „Advanced UV for Life" eingereicht hatte (siehe auch Schlaglichter, S. 21). In der Abteilung Wissenschaftsmanagement wurden die Ideen inhaltlich abgestimmt und Zuarbeiten von insgesamt 23 Partnern aus Wissenschaft und Industrie eingearbeitet und aufbereitet. Diese Koordination erfordert eine Vielzahl organisatorischer Aufgaben, die von Wissenschaftlern neben den eigentlichen F&E-Aufgaben kaum zu leisten sind. Durch die Einbindung des Wissenschaftsmanagements konnte der Aufwand einer solchen Wettbewerbsteilnahme für die Fachabteilungen des Instituts sowie für die beteiligten Partner auf das Notwendigste reduziert werden. In enger Abstimmung mit der Institutsleitung und in Zusammenarbeit mit dem Geschäftsbereich GaN-Optoelektronik und der Abteilung Materialtechnologie wurde das Konzept entwickelt. „Advanced UV for Life" konnte sich gemeinsam mit neun weiteren Konsortien unter insgesamt 59 Initialkonzepten durchsetzen. Der deutschlandweite Zusammenschluss widmet sich der Erforschung, Entwicklung und Anwendung von UV-LED-Technologien und wird bis 2020 mit bis zu 45 Millionen Euro gefördert. Davon profitieren auch die Forschungsarbeiten am FBH rund um UV-Leuchtdioden. Sie können hierdurch in den kommenden Jahren stark gestützt und bis zu konkreten Anwendungen, etwa in der Wasserentkeimung, vorangetrieben werden. Diese enge Vernetzung mit Partnern aus Forschung und Wirtschaft wie in „Advanced UV for Life" ist ein *grundlegender strategischer Ansatz des FBH, der die Sichtbarkeit des Instituts innerhalb des jeweiligen Themenfeldes zusätzlich erhöht. Daher hat das FBH auch 2013 seine Aktivitäten rund um die regionalen Technologie-Netzwerke Berlin WideBaSe, Zentrum für Mikrosystemtechnik Berlin (ZEMI) und des Kompetenznetzes Optische Technologien OpTecBB fortgeführt.*

Im Rahmen des Netzwerks Berlin WideBaSe, das als regionaler Wachstumskern über drei Jahre vom BMBF gefördert wurde, konnten neben den bereits laufenden Verbundprojekten, weitere Vorhaben in unterschiedlichen Kontexten gestartet werden. Nach dem Auslaufen der Finanzierung als Wachstumskern Mitte 2013 haben sich alle Partner für die weitere Zusammenarbeit unter der Dachmarke Berlin WideBaSe ausgesprochen. Ein konkretes Ergebnis ist das Konsortium „Advanced UV for Life“, bei dem viele WideBaSe-Partner beteiligt sind, eine andere Säule ist der seit 2012 laufende strukturierte Austausch mit polnischen Einrichtungen rund um Nitrid-Halbleiter. Dieser Austausch zwischen Berlin und Warschau – beides sind Zentren der Nitrid-Halbleiter-Forschung und -Entwicklung in Europa – wurde 2013 mit dem zweiten „German-Polish Workshop on Nitride-Semiconductors“ fortgeführt. Dieses Mal reisten die Berliner Kollegen nach Warschau. 80 Konferenzteilnehmer nutzten darüber hinaus die vom FBH im Herbst organisierte „2nd Berlin WideBaSe Conference on Technology and Applications of Nitride Semiconductors“ zur Fortbildung und zum Vertiefen der Kontakte.

Aktiv im Technologie- und Wissenstransfer

Im Bereich Technologietransfer unterstützte die Abteilung im vergangenen Jahr die Ausgründungsaktivitäten von Kolleginnen und Kollegen des FBH. In das Vorhaben BEAPLAS ist ein Mitarbeiter des Wissenschaftsmanagements direkt eingebunden und hilft dabei, den Businessplan zu entwickeln und die Geschäftstätigkeit aufzubauen. Die BEAPLAS GmbH entwickelt und vertreibt Verfahren und Anlagen für Dünnfilm-Beschichtung bei Atmosphärendruck. Zentrales Werkzeug ist eine Plasmaquelle, die in den letzten Jahren am FBH entwickelt und für verschiedene Anwendungen, von der Automobilfertigung bis zur Medizintechnik, optimiert wurde. Momentan wird dafür vor allem teure Vakuum-Technologie verwendet, die kostengünstigen atmosphärischen Werkzeuge sind daher auch kommerziell attraktiv. Das im Mai 2013 gegründete Spin-off wird von der Europäischen Union und dem Bundesministerium für Wirtschaft und Energie im Rahmen des EXIST-Forschungstransfer-Programms unterstützt.

^ Students at 8th Microsystems Summer School.
Studierende der 8. Microsystems Summer School.

Von der Berufsorientierung bis zur maßgeschneiderten Fortbildung: Bewährtes und neue Konzepte

Auch 2013 warb das Bildungsteam der Abteilung Wissenschaftsmanagement mit vielfältigen Aktivitäten bei Schülerinnen und Schülern, um sie für eine berufliche oder akademische Ausbildung im MINT-Bereich (Mathematik – Informatik – Naturwissenschaften – Technik) zu begeistern. Nach wie vor sind viele interessante und zukunftsorientierte Bildungs- und Karrieremöglichkeiten in der Hochtechnologie bei jungen Menschen weitgehend unbekannt. Neben der Berufsorientierung rückte der Bereich der betrieblichen Weiterbildung stärker in den Fokus: Hier zeichnet sich infolge des schnellen technologischen Wandels eine Lücke zwischen Weiterbildungsangeboten und dem speziellen Bedarf von Unternehmen ab. Zur Werbung von qualifiziertem Nachwuchs hat das FBH seine Zusammenarbeit mit Schulen weiter ausgebaut und intensiv über berufliche und akademische Bildungsmöglichkeiten informiert. Neue Kooperationen wurden unter anderem im „Berliner Programm

^ Soldering is fun – girls are testing their technical skills.
Löten macht Spaß – Mädchen testen ihre technischen Talente.

für vertiefte Berufsorientierung" geschlossen. In enger Zusammenarbeit mit ZEMI, dem Zentrum für Mikrosystemtechnik Berlin und OpTecBB, dem Kompetenznetz Optische Technologien aus Berlin und Brandenburg, wurden weitere Aktivitäten initiiert, die über Karrieremöglichkeiten in der Mikrosystemtechnik informieren. Dazu gehörte auch die Teilnahme an verschiedenen Messen und Ausstellungen.

Ein besonderes Highlight des Jahres 2013 war der 4. Mädchen-Technik-Kongress, den das Bildungsteam im Rahmen des bundesweiten Netzwerkes mst|femNet meets Nano and Optics organisiert hat. In diesem Jahr fand die vom BMBF (Bundesministerium für Bildung und Forschung) geförderte eintägige Veranstaltung im Wissenschafts- und Technologiepark Berlin-Adlershof statt. Das FBH wurde dabei von vielen lokalen und regionalen Akteuren unterstützt, die praktische Workshops oder Führungen über den Campus angeboten haben. Die Schülerinnen besuchten Unternehmen, Forschungseinrichtungen und historische Sehenswürdigkeiten aus der Forschung wie den Windkanal, die Kugellabore und das alte Flugfeld. Etwa 170 Berliner und Brandenburger Mädchen von der 7. bis zur 12. Klasse hatten die Wahl zwischen zahlreichen Workshops und praktischen Experimenten. Sie erhielten so Einblicke in den Berufsalltag von Wissenschaftlern und Wissenschaftlerinnen sowie technischen Beschäftigten. Eine Weiterbildung für Lehrkräfte ergänzte das Programm. Darüber hinaus initiierte das FBH verschiedene Runde Tische, um das Netzwerk von Multiplikatoren und Multiplikatorinnen auszubauen und zu verstetigen. Es informierte dabei über Karriereoptionen und Ausbildungsmöglichkeiten in der Mikrosystemtechnik und den Optischen Technologien und band die Gender-Thematik stärker in die MINT-Aktivitäten ein. Zudem wurde begonnen, den bewährten Mädchen-Technik-Kongress als Good Practice-Beispiel in europäische Nachbarländer zu transferieren und das Konzept zugleich mit neuen Ideen und Erfahrungen aus anderen europäischen Ländern zu erweitern. Im Januar 2014 startet dazu ein FP7-Projekt zur Nachwuchsgewinnung im Bereich Photonik.

Die 8. Mikrosystemtechnik Sommeruniversität und das 2. Doktorandenforum der Sektion D der Leibniz-Gemeinschaft wurden ebenfalls durch die Abteilung Wissenschaftsmanagement organisiert. Seminare, Fachvorträge sowie Instituts- und Betriebsbesuche in Hochtechnologie-Laboren sorgten für ein breites und abwechslungsreiches Programm. Die traditionelle Abendveranstaltung „Summer School meets Company" nutzen die Teilnehmenden, um Kontakte mit Vertretern und Vertreterinnen aus den ZEMI-Instituten und Unternehmen zu knüpfen. Hierbei ging es sowohl um den fachlichen Austausch als auch um die Unterstützung bei Bachelor- und Master-Arbeiten.

2013 analysierte die Abteilung Wissenschaftsmanagement zudem im Auftrag der Senatsverwaltung für Wirtschaft, Technologie und Forschung den aktuellen Weiterbildungsbedarf von Unternehmen aus den Optischen Technologien und der Mikrosystemtechnik. Dazu wurden Verantwortliche aus der Geschäftsführung und dem Personalbereich aus mehr als 20 Einrichtungen befragt. Die Umfrage ergab, dass zusätzlich zu herkömmlichen Weiterbildungsangeboten, ein Interesse an maßgeschneiderten Trainingseinheiten besteht, die jeweils für einen sehr begrenzten Personenkreis relevant sind. Eine weitere Erkenntnis ist, dass bestehende Ressourcen und Kompetenzen beim Ausbau der Kooperationen zwischen Forschungseinrichtungen und Unternehmen effektiver genutzt werden können.

Microwave Components & Systems
Mikrowellenkomponenten & -systeme

Business Areas & Research
Geschäftsbereiche & Forschung

Die übergeordnete Zielsetzung des FBH im Bereich der Mikro- und Millimeterwellen ist es, die Grenzen der elektronischen Bauteile hinsichtlich effizienter Leistungserzeugung bei hohen Frequenzen systematisch zu erweitern. Dies geschieht auf Basis der III/V-Halbleitertechnologie und verfolgt die folgenden drei Forschungslinien:

- *Die Effizienz der Leistungserzeugung im Mikrowellenbereich weiter zu steigern, speziell in den Frequenzbändern, die für die drahtlose Kommunikationsinfrastruktur genutzt werden. Basis dafür ist die GaN-Technologie. Dies umfasst auch neuartige Architekturen wie den Klasse-S-Ansatz.*
- *Die verfügbare Ausgangsleistung im Frequenzbereich oberhalb 100 GHz bis (momentan) 250 GHz mithilfe von InP-Heterobipolartransistoren zu erhöhen. Dies beruht auf einem Transfer-Substrat-Prozess und beinhaltet auch eine InP-auf-BiCMOS-Heterointegration auf Waferebene, die gemeinsam mit dem Leibniz-Institut für innovative Mikroelektronik entwickelt wurde.*
- *Die Anwendung von plasmonischen Effekten für die Terahertz-Detektion und -Emission zu erkunden. Diese Phänomene versprechen eine Einsatzmöglichkeit von Transistorstrukturen weit oberhalb der klassischen Grenzfrequenzen im 1 THz-Bereich. Wir nutzen dazu die GaN-Technologie.*

Neben der III/V-Halbleitertechnologie erfordern diese Forschungsarbeiten die entsprechende Expertise bei Simulation, Design und Charakterisierung. Diese ist am FBH verfügbar und wird kontinuierlich weiterentwickelt. Eine umfangreiche Messtechnik ermöglicht die Charakterisierung der Bauelemente bis zu Frequenzen von 500 GHz. Somit stellt das FBH die gesamte Wertschöpfungskette bereit, von Epitaxie und Prozessierung bis zu Design, Mess- und Aufbautechnik.

Die Forschungsarbeiten adressieren Schlüsselkomponenten für die drahtlose Kommunikationsinfrastruktur, wie Basisstationen für die Mobilkommunikation, sowie für Radar- und bildgebende Systeme. Darüber hinaus nutzt das FBH seine Kompetenz auf dem Gebiet der Komponenten, um einzigartige System-Funktionsblöcke für spezielle Anwendungen zu entwickeln. Im Einzelnen umfasst das FBH-Forschungs-Portfolio die folgenden Themen:

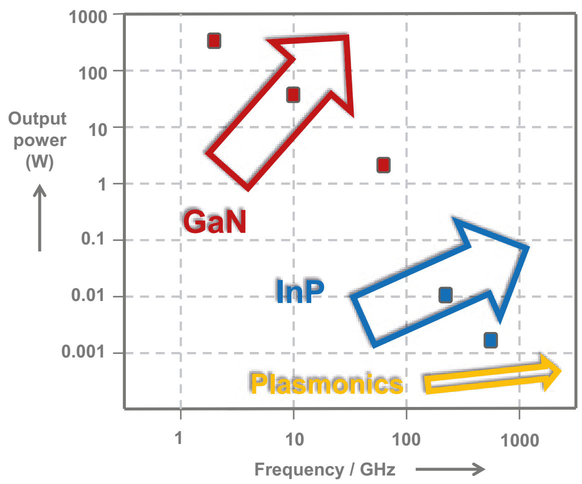
- *Diskrete GaN-Hochleistungs-Transistoren (HEMTs) und -MMICs für Frequenzen von 1 bis 20 GHz und den Leistungsbereich von 10 bis 100 W, einschließlich robuster rauscharmer GaN-MMIC-Verstärker,*
- *Auf dem Weg zum digitalen Mikrowellen-Leistungsverstärker: Klasse-S-Module mit GaN-Leistungs-MMICs für den Frequenzbereich 1…2 GHz,*
- *InP-HBT-MMICs für Betriebsfrequenzen von 100 GHz und darüber, auf AlN-Substrat und als InP-auf-CMOS-Lösung,*
- *GaN-basierte Bauelemente für plasmonische Emission und Detektion bei THz-Frequenzen,*
- *Kompakte integrierte Mikrowellen-Quellen zur Plasmaerzeugung im 2 GHz-Bereich,*
- *Schnelle Treiber für Leistungs-Laserdioden und elektro-optische Modulatoren.*

Die zugehörigen GaN- und InP-Prozesse werden von den Technologieabteilungen des FBH beziehungsweise dem Geschäftsbereich GaN-Elektronik entwickelt und gepflegt. Reinraumlabore mit industriekompatiblem Gerätepark ermöglichen es, Bauelemente auf dem neuesten Stand der Technik herzustellen.

Microwave Components & Systems
Mikrowellenkomponenten & -systeme

The overall target of the FBH in the microwave and mm-wave field is to push the limits of electronic devices with regard to power and efficiency at high frequencies. This is based on III-V semiconductor technology and pursued in three different directions:

- Advancing the power-efficiency performance at microwave frequencies, particularly in the bands used for the wireless infrastructure. This relies on gallium nitride (GaN) components and includes development of novel microwave power amplifier (PA) architectures such as the class-S approach.
- Increasing the available output powers for frequencies beyond 100 GHz up to, so far, 250 GHz, by using indium phosphide (InP) bipolar transistors (HBTs). A transferred-substrate process is applied which includes a wafer-scale InP-on-BiCMOS heterointegration option, which has been developed with the Leibniz-Institut für innovative Mikroelektronik.
- Exploring plasmonic effects for THz detection and emission. These phenomena promise device operation well beyond the classical frequency limits and thus open up possibilities for electronic components in the 1 THz range. We use GaN as semiconductor for these developments.



Besides the III-V semiconductor technologies, these activities require the corresponding advanced simulation, design, and measurement expertise which is available at FBH and continuously developed further. Dedicated measurement equipment allows characterization for frequencies up to 500 GHz. This way, the FBH offers the entire value-added chain from epitaxy and processing to computer-aided design, measurements, and packaging.

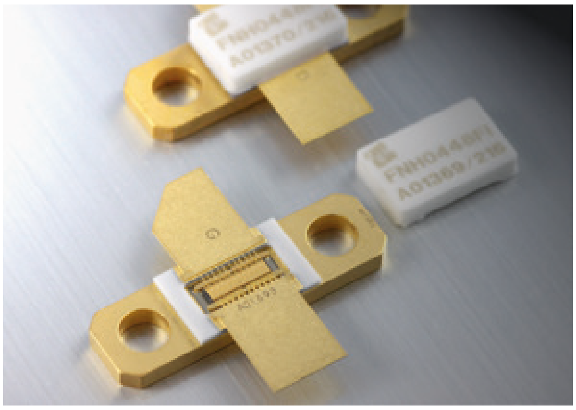
FBH research work addresses key components for the wireless communications infrastructure, such as cellular radio base-stations, and for radar and imaging systems. Beyond this, the institute's competence is used in components to develop unique system function blocks for special applications. In more detail, the FBH research portfolio in the microwaves field comprises the following topics:

- GaN high-power discrete transistors (HEMTs) and MMICs for 1 to 20 GHz with 10 to 100 W output power; this covers also robust low-noise GaN amplifier MMICs,
- Towards the digital microwave PA: S-class modules with GaN MMICs for the 1…2 GHz frequency range,
- InP-HBT MMICs for operation at frequencies of 100 GHz and beyond, on AlN substrate and as InP-on-BiCMOS solution,
- GaN-based devices for plasmonic emission and detection of THz frequencies,
- Compact integrated microwave sources for microplasma generation (2 GHz range),
- High-speed drivers for power laser diodes and for electro-optical modulators.

The relevant GaN and InP processes are developed and maintained by FBH's technology departments and the GaN Electronics Business Area, respectively. Cleanroom laboratories with industry-level equipment offer the capabilities required for state-of-the-art device performance.

GaN microwave power transistors – optimization, characterization, and modelling

There is a general trend towards moving up in frequency with modern wireless telecommunication standards, populating also the bands between 2 GHz and 6 GHz. This trend is driven by the increasing amount of information to be transmitted, particularly since smart phones with video communication capabilities and constant internet access are in wide use. Advanced standards like Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) work with large modulation bandwidths in the 10 - 60 MHz range at frequencies well above 2.5 GHz. This places new demands on the hardware used in the systems. FBH is developing a key component targeting this cellular infrastructure market, the power transistor, a discrete gallium nitride high electron-mobility transistor (GaN-HEMT, see Fig. 1).

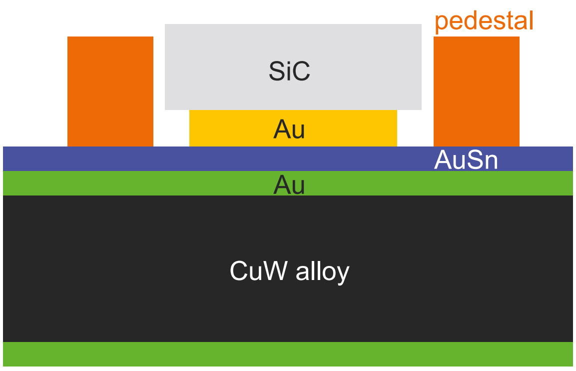


∧ **Fig. 1.** Packaged GaN-HEMT powerbars targeting 2.5+ GHz applications.

Beyond communications, there are further interesting applications in radar systems around 3.5 GHz and above as well as in the 2.45 GHz ISM band, e.g., power generators for microplasma sources. They all require appropriate power transistors in the 50…150 W range at frequencies exceeding those of the conventional communication bands below 2 GHz.

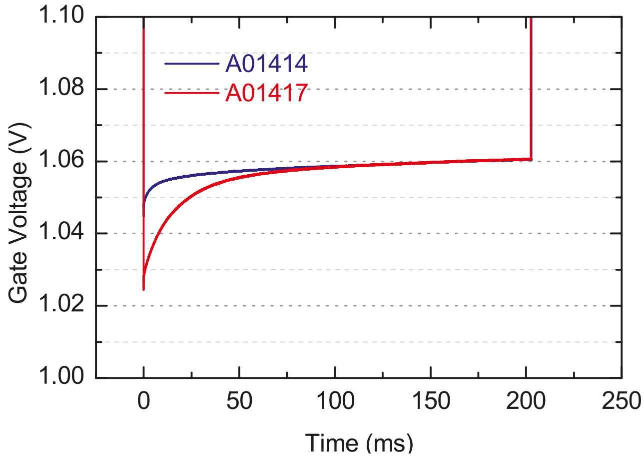
With this motivation, FBH has extended its activities on optimizing discrete GaN-HEMTs, targeting now also the bands up to 5 GHz. Moving up in frequency poses new challenges in power transistor development: Power gain decreases while parasitics of the internal transistor, and particularly those related to the packaging, increase. At 3.5 GHz, the packaged 50 W transistors reach efficiency (PAE) values of about 55% in compression. To further improve the device, extensive characterization of electrical and thermal properties is needed. Furthermore, the transistor itself must be optimized, along with the package design and the packaging method. This requires proper description by non-linear models, which are also provided to engineers using the FBH components in their designs.

GaN is a semiconductor material that has a very high breakdown voltage combined with a high current density. Realized on a SiC substrate, this enables high-frequency components with high power density. At higher frequencies, the transistor operates less efficiently and more heat needs to be removed. A cross-section of a packaged device is shown in Fig. 2. For good heat dissipation, first the design of the transistor chip itself is important. However, due to the excellent heat conductance of the SiC substrate, soldering of the chips and the flange properties also play an important role in the overall thermal performance.

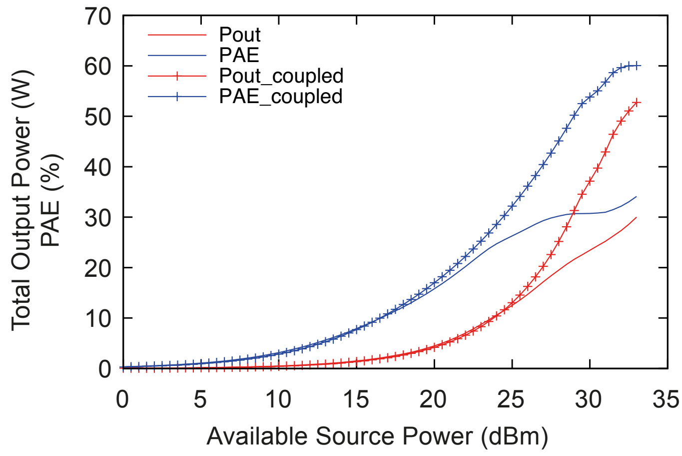


∧ **Fig. 2.** Cross-section of a packaged GaN-HEMT powerbar.

To determine the thermal properties several methods are applied. First, the heat-spreading is analyzed qualitatively using thermal infrared (IR) imaging. Furthermore, non-destructive ultrasound investigations are used to verify the quality of the chip soldering. The high acoustic contrast between air/oxide and metal gives a clear fingerprint of the soldering quality. Recently, an additional method for electrical characterization of the thermal resistance has been developed. It is fast, non-destructive, and provides quantitative data. The method is based on pulse measurements, exciting the GaN transistor with an electrical pulse on the drain. This heats the transistor instantaneously. On the falling edge of the pulse the cooling of the transistor is monitored through the temperature-dependent gate-diode voltage. The temperature characteristics of the diode are pre-characterized, thus the calibrated channel temperature can be measured over the full cooling cycle. From this data the thermal



∧ **Fig. 3.** Pulse response results for thermal characterization from two different transistors.



∧ **Fig. 4.** Simulated total output power and PAE of a powerbar without and with cell coupling through ballasting resistors.

resistance as well as the thermal time constant of different layers can be extracted. This method is less sensitive to trapping effects than other methods, which makes it very suitable for characterization of GaN transistors. Typical results are shown in Fig. 3, where a powerbar with low thermal resistance (in blue) can clearly be distinguished from a powerbar with high thermal resistance (in red). These methods are employed altogether when optimizing the different steps in the mounting process of the GaN-HEMT powerbars.

The thermal results are also used in device modelling. A comprehensive electro-thermal model for power transistors is now available to meet the needs of transistor designers. At higher frequencies, the electro-thermal interaction of the cells in the package becomes more complex and a more advanced model is necessary. Our powerbar model comprises an RF package model, a network describing the thermal properties as well as the thermal coupling between the cells, and the non-linear large-signal transistor models of the individual power cells. It allows simulation of the DC and radio-frequency power distribution as well as the temperature distribution within the powerbar. With this comprehensive model the interaction of the individual parts within the powerbars can be better understood. It is useful, for instance, when designing ballasting resistors between the cells. Fig. 4 illustrates, how in this way the operation of a 11-cell powerbar can be stabilized, which boosts output power and PAE by almost a factor of 2.

The activities were funded by the Federal Ministry of Education and Research within the innovative regional growth core Berlin WideBaSe.

Der Trend bei neuen Mobilfunkstandards wie LTE und WiMAX geht zu höheren Frequenzen im Bereich von 2 bis 5 GHz. Das stellt neue Herausforderungen an die mobile Infrastruktur. Dafür werden Leistungstransistoren im Bereich von 50 bis 150 W benötigt. Das FBH hat deshalb seine Aktivitäten auf dem Gebiet der diskreten GaN-HEMT-Transistoren entsprechend erweitert. Aufgrund des niedrigeren Wirkungsgrades bei höheren Frequenzen ergeben sich höhere Anforderungen hinsichtlich der elektrischen und thermischen Eigenschaften der Transistoren. Zur Messung des thermischen Widerstandes setzt das FBH neben einer Wärmebildkamera und Ultraschall ein selbst entwickeltes elektrisches Pulsverfahren ein. Darüber hinaus wird ein neues elektro-thermisches Modell bei der Transistorentwicklung verwendet, das die nichtlinearen Eigenschaften der Transistorzellen, deren Zusammenschaltung im Gehäuse sowie das thermische Verhalten einschließlich der thermischen Kopplungen erfasst.

Publications

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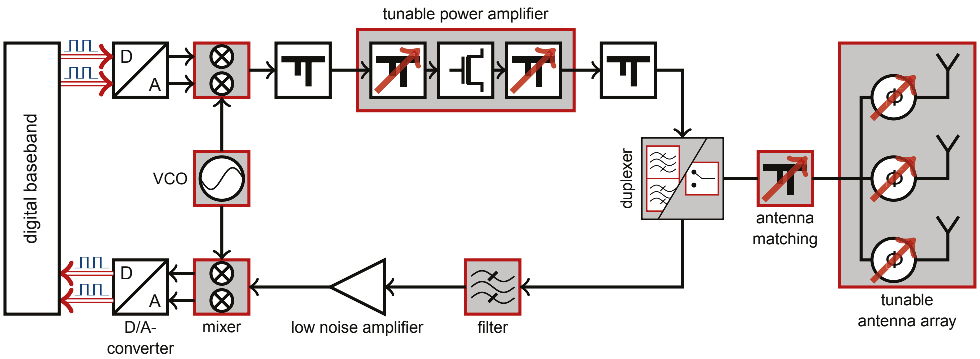
F. Schnieder, O. Bengtsson, F.-J. Schmückle, M. Rudolph, W. Heinrich, "Simulation of RF power distribution in a packaged GaN power transistor using an electro-thermal large-signal description", IEEE Trans. Microw. Theory Techn., vol. 61, no. 7, pp. 2603-2609 (2013).

Tunable matching of microwave power transistors using BST varactors for load modulation and frequency-agile systems

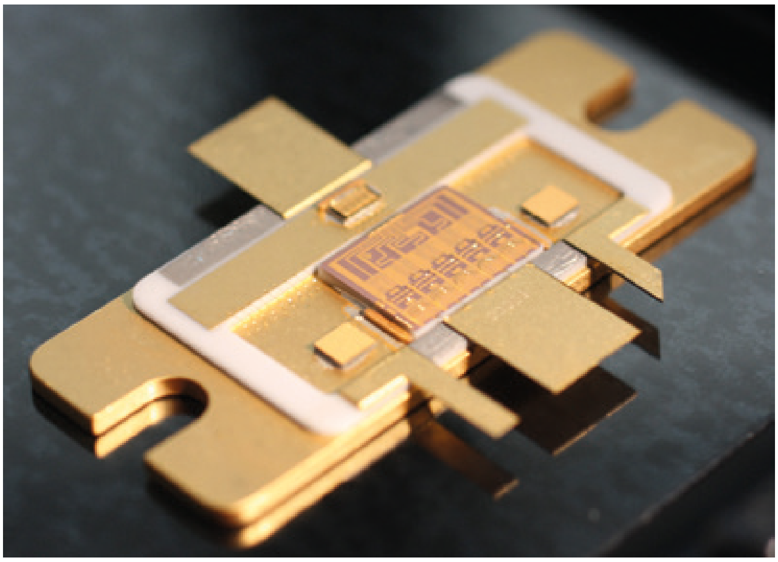
The border between wireless computer communication, such as WLAN and WiMAX, and cellular systems like UMTS and LTE is vanishing. Thus, future wireless telecommunications systems will have to work with many standards in various frequency bands, covering the full 500 MHz to 6 GHz range. A viable emerging alternative to today's parallel systems are frequency-agile reconfigurable systems as illustrated by Fig. 1. Tunable components placed at critical points in the system enable electrical retuning for frequency modification or performance optimization. Such systems have been implemented mostly with tunable matching networks based on semiconductor varactor diodes or micro-electromechanical system components (MEMS), in combination with conventional discrete transistors.



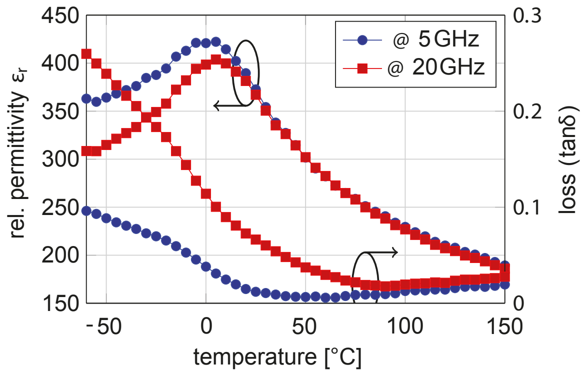
∧ **Fig. 1.** Reconfigurable transceiver architecture based on tunable components.

The Ferdinand-Braun-Institut together with the Technische Universität Darmstadt is developing an alternative solution based on novel discrete tunable pre-matching (TpM) RF-power transistors. The TpM transistor consists of a GaN-HEMT combined with thick-film barium-strontium-titanate (BST) tunable pre-matching networks, integrated into a single package. This solution enables pre-matched discrete RF-power transistors that can be tuned for multi-band operation, for improved in-band performance, and for increased back-off efficiency through load modulation. As the ceramic material BST shows a field-dependent permittivity, it can be exploited to realize tunable microwave components such as varactors.

The thick-film BST components in this work are fast to tune and show high linearity, features that are required in many power amplifier applications. Size and power handling capabilities also make them very suitable to be integrated into a package with a RF-power GaN transistor (see Fig. 2). A key issue that is presently addressed at the FBH is the temperature dependence of BST shown in Fig. 3. The relatively high losses in the BST varactor cause self-heating, which leads to self-tuning. This, in effect, reduces the tuning range. Optimized material doping, improved packaging with better heat-sinking, and novel low-loss varactor topologies are used to address this issue.

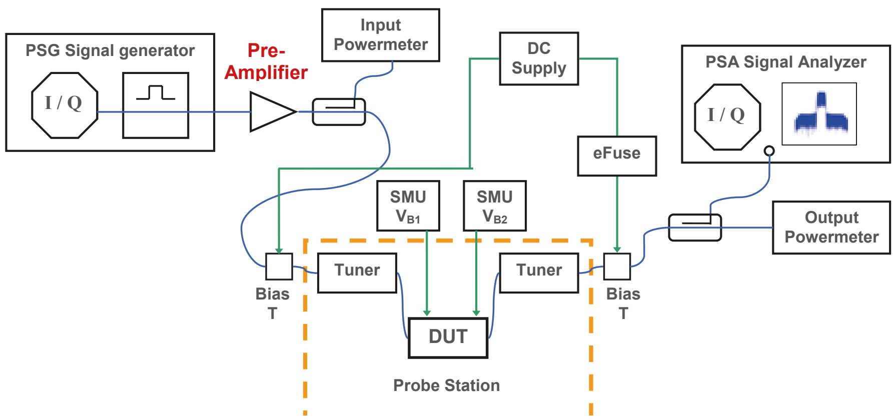


∧ **Fig. 2.** Fabricated 5-cell TpM transistor.



^ **Fig. 3.** Temperature-dependent permittivity of BST.

Within this project, FBH is responsible for TpM package integration along with large-signal thermal and electrical characterization of single BST varactors, hybrid GaN-BST units, and discrete packaged tunable pre-matching transistors. This includes large-signal time-domain characterization as well as linearity characterization using modulated signals. The measurements are conducted in a modified load-pull system presented in Fig. 4, where the individual varactors can be separately adjusted during load-pull. Efforts at FBH also involve the future use of these tunable pre-matching transistors in amplifier demonstrators. The project is conducted in close cooperation with the Institute of Microwave Engineering and Photonics at Technische Universität Darmstadt, where the varactors are fabricated, characterized, and modelled. The ceramic BST material is manufactured at the Karlsruhe Institute of Technology (KIT).



^ **Fig. 4.** System for large-signal characterization.

Immer leistungsfähigere Smartphones lassen die Grenze zwischen drahtloser Kommunikation von Computern (WLAN, WiMAX) und zellularen Systemen wie UMTS und LTE verschwimmen. Daraus ergeben sich höhere Anforderungen an die Infrastruktur der Mobilkommunikation: Sie muss kompatibel sein mit mehreren Kommunikationsstandards und mit Signalen, die über den kompletten Frequenzbereich von 500 MHz bis 6 GHz verteilt sind. Das Ferdinand-Braun-Institut entwickelt daher in Zusammenarbeit mit der TU Darmstadt einen neuartigen Mikrowellen-Leistungstransistor, der die Möglichkeit eines abstimmbaren Pre-Matching bietet. Ein GaN-HEMT wird dazu zusammen mit einem Barium-Strontium-Titanat-Netzwerk im Gehäuse integriert. So können Leistungstransistoren hergestellt werden, die für den Betrieb auf mehreren Frequenzbändern dynamisch eingestellt werden können. Außerdem ist damit eine Lastmodulation möglich, um etwa den Wirkungsgrad bei niedrigen Ausgangsleistungen zu verbessern. Ein besonderer Fokus liegt dabei zurzeit auf thermischen Untersuchungen.

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A. Wiens, O. Bengtsson, H. Maune, S. Sazegar, W. Heinrich, R. Jakoby, "Thick-Film Barium-Strontium-Titantate Varactors for RF-Power Transistors", European Microwave Conference (EuMC) digest, pp. 1351-1354, Nuremberg, Germany (2013).

Towards the digital power amplifier for the future wireless infrastructure

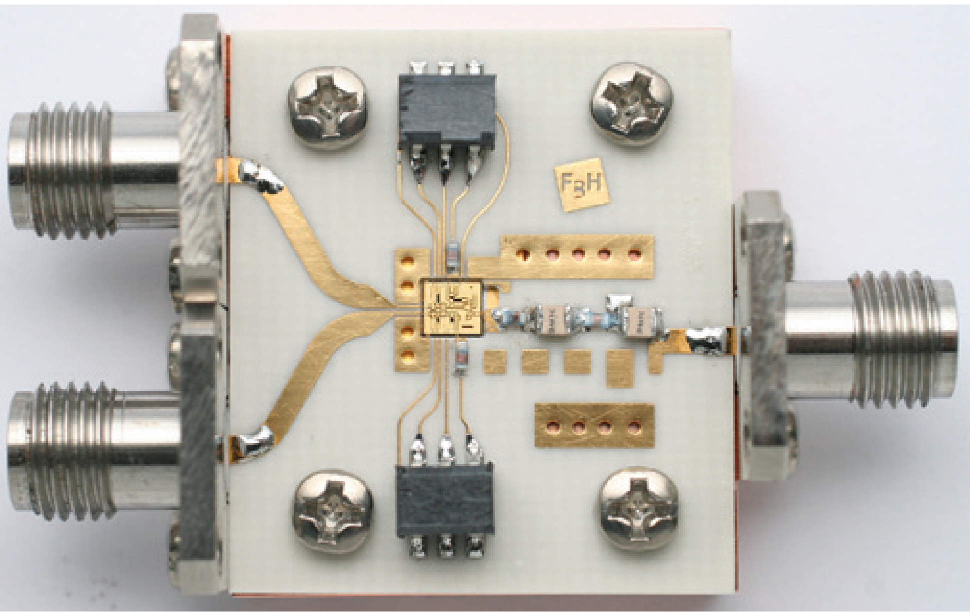
Today`s wireless and mobile network infrastructure is facing continuously growing demands. These include particularly cost-effective management of high data-traffic growth rates and broadband internet access everywhere. New communication standards like HSPA+ and LTE are evolving towards higher bandwidth requirements and flexibility, setting the scene for the future wireless infrastructure. The more, this has to be accomplished in an energy-efficient way to meet the mission statement of a "green IT".

As the RF-power amplifier (PA) is one of the most power consuming parts in a base station, a key parameter to be optimized is the power-added efficiency (PAE) of these PAs. At the same time, operators are targeting transmitters with an increased digital content in order to enhance hardware flexibility, to simplify architecture, to improve compactness, and to reduce cost. In this regard, the digital PA concepts like class-D and class-S have proven to be suitable candidates. FBH has been contributing leading-edge results in this field over the past years, using GaN-based MMICs.

The major drawback of the microwave digital power amplifier realizations so far is the low overall PAE. Although showing very high final-stage drain efficiencies, the PAE values including driver and pre-driver did not yet reach a competitive level compared to the more conventional amplifier concepts. Another particular challenge for these types of PAs is the reconstruction filter. Stringent requirements in terms of low insertion loss, high selectivity, broadband input impedance behavior, operation in a non-50 Ω environment, and compactness must be fulfilled.

In 2013, work on this topic at FBH focused on these two directions: First, a PAE optimized voltage-mode class-D (VMCD) PA module and second, a highly selective but compact third-order lumped-element reconstruction filter (trisection filter), each optimized for the LTE frequency band of 800 MHz. The amplifier module realized is shown in Fig. 1 (PAE-optimized class-D PA), while Fig. 2 displays the trisection filter topology (left) and the fabricated prototype (right).

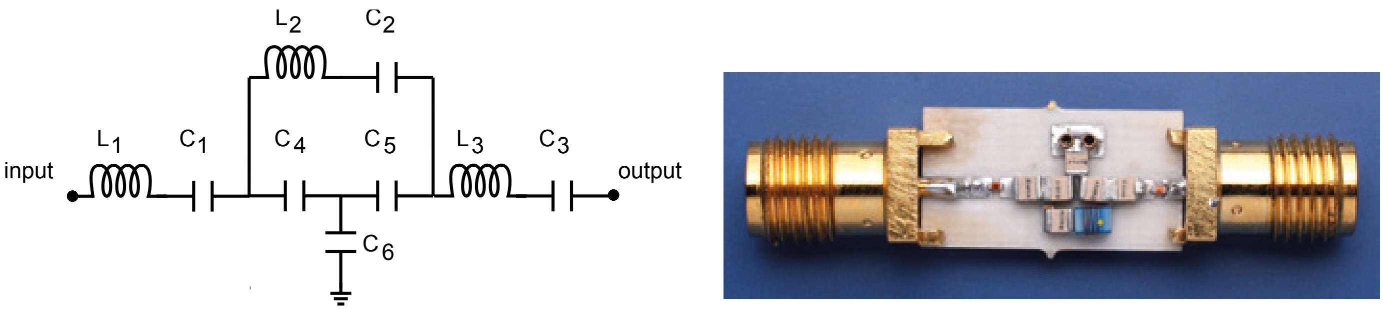
The compact PAE-optimized VMCD PA module comprises a 3-stage GaN MMIC, external inductance circuitry, and a lumped output network. Basically, the introduction of external lumped inductors to drive the push-pull final-stage GaN HEMTs reduces the dissipated DC power drastically so that the overall PAE could be significantly improved by at least



< Fig. 1. Realized PAE optimized voltage-mode class-D PA module for the 800 MHz band; size: 22 x 25 x 9 mm³.

40 percentage points. For a maximum overall PAE of 59% the saturated output power P_{out} is 5.2 W. Final-stage drain efficiency stays almost constant over the whole supply voltage range up to 40 V with values of around 80%. Large-signal gain at maximum P_{out} is above 20 dB. This performance sets new record values for this type of PA. While overall PAE was never seriously considered and optimized in previous VMCD realizations for the microwave frequency range, the results prove for the first time that one can indeed achieve overall efficiencies which compare well with other more conventional concepts.

The filter design started from the trisection filter topology, with focus on a compact solution. The latter is mandatory due to the broadband operation mode. Thus, a connection of short electrical length between PA output and filter input is strictly required in order to prevent impedance transformations which would strongly affect digital PA performance. After the synthesis procedure, the final compact filter network shown in Fig. 2 (left) was found to be a good candidate for the reconstruction filter of the targeted digital PAs (voltage-mode class-D/S type).



∧ **Fig. 2.** Trisection bandpass filter configuration (l.) and fabricated prototype (r.).

The proposed filter (Fig. 2, right) was simulated and successfully realized, achieving an insertion loss of 0.8 dB and an input return loss of 17 dB minimum. Also, it fulfills the tough broadband input impedance requirements down to the kHz-range and up to 4 GHz and beyond. This deviates from common filter designs, but needs to be considered for the special application in digital PAs (class-D/S). The designed filter introduces a transmission zero in the upper frequency band to suppress unwanted spectral components. This improves linearity of the targeted class-D/S power amplifiers.

Seit mehreren Jahren realisiert das FBH digitale Mikrowellen-Schaltverstärkerkonzepte (Klasse-D, -S), die auf GaN-MMICs basieren. Sie liefern die Voraussetzungen für zukünftige Mobilfunk-Basisstationen mit optimierter Effizienz und Flexibilität. 2013 ist es erstmals gelungen, die Gesamteffizienz (PAE) dieser Schaltverstärker auf 59% zu erhöhen. Darüber hinaus wurden neue Filterkonzepte mit verbesserter Trennschärfe umgesetzt: Dabei wurden ein PAE-optimierter Voltage-Mode-Klasse-D-Verstärker und ein hoch selektives Filter dritter Ordnung mit konzentrierten Elementen realisiert, jeweils für das 800-MHz-Frequenzband. Der Klasse-D-Verstärker erreicht eine maximale PAE von 59% bei einer Spitzenausgangsleistung von 5 W. Das beweist erstmals, dass digitale Schaltverstärker Gesamteffizienzen im Bereich konventioneller HF-Verstärker erreichen können. Das realisierte Filter zeigt eine Einfügungsdämpfung von 0,8 dB bei der Signalfrequenz und eine Reflexionsdämpfung von minimal 17 dB. Durch eine Übertragungsnullstelle im oberen Frequenzband werden Trennschärfe und Linearität des digitalen Verstärkers wesentlich verbessert.

Publications

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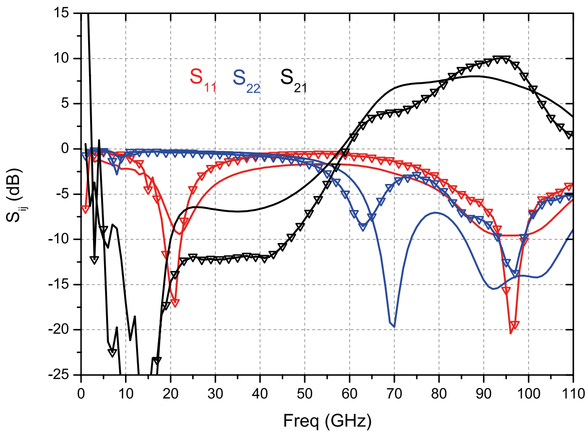
A. Wentzel, W. Heinrich, "A GaN Voltage-Mode Class-D MMIC with Improved Overall Efficiency for Future RRH Applications", Proc. 43th European Microwave Conf. (EuMC 2013), Nuremberg, Germany, Oct. 7-10, pp. 549-552 (2013).

InP HBT-based circuits for the 200 GHz frequency band

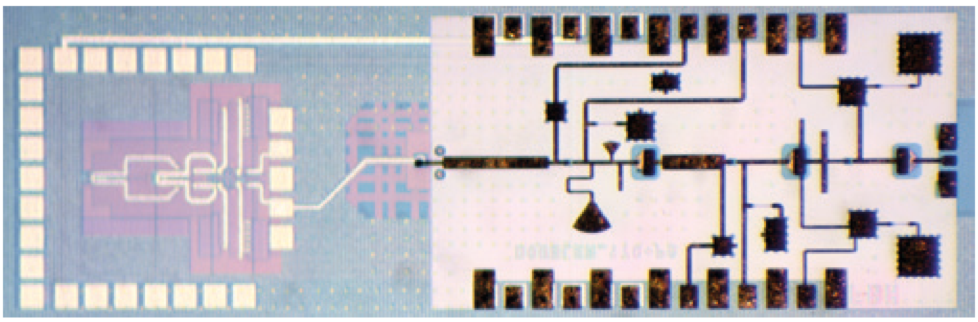
We have successfully expanded our MMIC circuit design to frequencies above 200 GHz and to more complex functionalities. The focus has been to push current performance limitations, mainly in the area of signal generation and power amplification. The in-house InP transferred-substrate DHBT process has been employed for oscillators reaching 200 GHz and power amplifiers operating up to around 180 GHz. We have also successfully combined this technology with the BiCMOS process of Leibniz-Institut für innovative Mikroelektronik through wafer-level heterointegration. This combination allows to realize more complex mixed-signal compact circuits on the same chip. The novel InP-on-BiCMOS MMIC process features wafer-level integration and optimized via interconnect technology capable of operation up to terahertz frequencies (see also p. 124).



< Fig. 1. Comparison of measured and simulated small-signal characteristics of a two-stage power amplifier at W-band: S-parameters versus frequency.

The following MMICs have been realized:

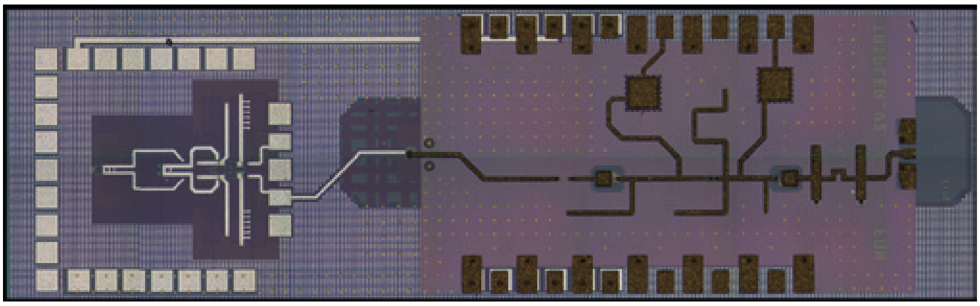
- Oscillator signal sources at 100 GHz, 200 GHz, 300 GHz with measured phase noise below -90 dBc/Hz at 1 MHz and more than 0 dBm output power,
- Power amplifiers for frequencies between 48 and 180 GHz with P_{out} up to 23 dBm and efficiencies above 20%,
- Frequency multipliers at 164 GHz and 180 GHz (doublers), with P_{out} beyond 3 dBm, and at 240 GHz (tripler) with P_{out} exceeding 0 dBm.



∧ Fig. 2. 164 GHz frequency doubler using the InP-on-BiCMOS MMIC process.

An oscillator signal source operating at 197 GHz with a high efficiency of 4.5% and a DC consumption of only 22 mW has been realized with an output power of 0 dBm and a phase noise of -88 dBc/Hz at 1.6 MHz offset frequency.

With regard to power amplifiers, Fig. 1 exemplarily shows simulated and measured S-parameters for a two-stage power amplifier at W-band with a small-signal gain above



∧ Fig. 3. 250 GHz frequency tripler using the InP-on-BiCMOS MMIC process.

10 dB and more than 10 % relative bandwidth. Large periphery power stages demonstrated an output power P_{out} of 19 dBm and 4 dB associated gain.

Various frequency multipliers have also been realized, including a 180 GHz frequency doubler in transferred-substrate InP DHBT process. This device exhibits state-of-the-art performance with a maximum output power of 4 dBm and 9.6 dB conversion loss at 180 GHz, while it achieves 7 dBm at 160 GHz and 2.6 dBm at 220 GHz, respectively. The optimum conversion loss for the full 160 - 220 GHz range is better than 6 dB. The circuit utilizes a 2-finger HBT with 0.8 × 5 μm^2 emitter size, the total circuit area is 0.83 μm^2.

A hetero-integrated InP-on-BiCMOS MMIC frequency doubler at 164 GHz and a tripler at 250 GHz are depicted in Figs. 2 and 3, respectively. Both multipliers are combined with a BiCMOS VCO, thus forming a complete signal source. The 164 GHz doubler shows an output power around 0 dBm, with the on-chip VCO delivering less than 5 dBm at 82 GHz. Output powers above 3 dBm at 164 GHz would be possible with a more powerful source or an additional power amplifier at the input of the doubler circuit. This circuit has won the Best Paper Award at the 2013 EuMIC conference. The frequency tripler shown in Fig. 3 operates between 240 - 250 GHz and utilizes the same technology. It generates an output power of -10 dBm driven by the same 82 GHz VCO. Power consumption of the tripler is 10.6 mW and fundamental and second harmonic signal are suppressed by more than 25 dB at the tripler output. This is the first hetero-integrated high-speed signal source beyond 200 GHz reported so far.

Part of the work was supported by the Leibniz Association within the SciFab and HiTeK projects and by the German Space Agency DLR, project mmRadar4Space (ID 50 RA 1103).

Das FBH hat seine Aktivitäten im Hinblick auf MMICs mit komplexeren Funktionalitäten und für Frequenzen oberhalb von 200 GHz ausgeweitet. Damit wurden die Betriebseigenschaften deutlich verbessert und neue MMIC-Technologien am FBH etabliert. Ausgehend von dem bisherigen InP-DHBT-Prozess in Transfer-Substrat-Technologie wurde in Zusammenarbeit mit dem Leibniz-Institut für innovative Mikroelektronik ein InP-on-BiCMOS-Prozess mithilfe von Wafer-Level-Heterointegration entwickelt. Dieser wurde erfolgreich bis zu höchsten Frequenzen getestet. Der Prozess verfügt auch über breitbandige verlustarme Verbindungen zwischen den SiGe- und InP-Schaltungsteilen. Es wurden sowohl Oszillatoren als auch Frequenzvervielfacher bei über 240 GHz realisiert und charakterisiert. Breitbandige Leistungsverstärker bei Frequenzen bis 110 GHz mit Leistungen von über 18 dBm wurden demonstriert, ebenso wie Verstärker bis 180 GHz mit einer Verstärkung von etwa 5 dB.

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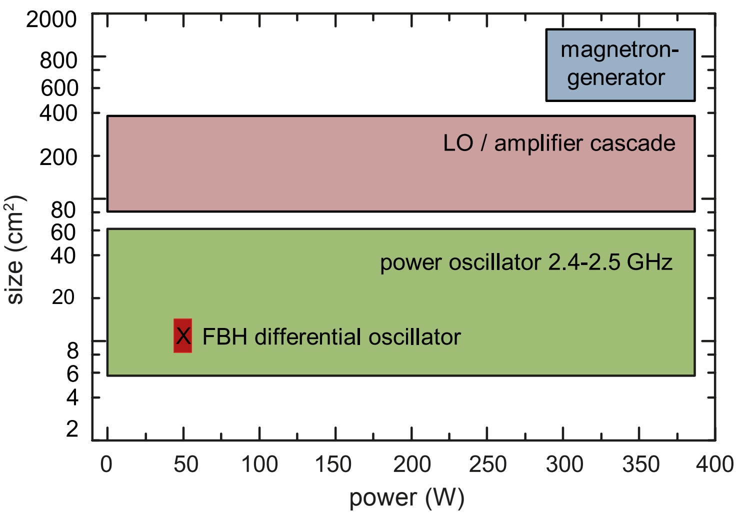
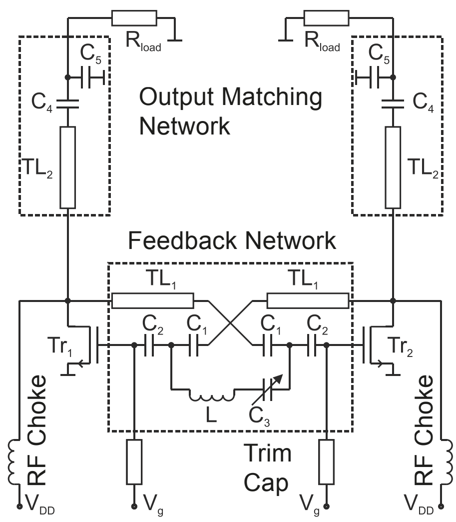
Compact microwave power oscillators for integrated microplasma sources

Microplasma sources can ionize gases in a very concentrated plasma-jet. This enables the controlled synthesis of chemical processes on any type of surface. A variety of applications exploiting this capability are just about to be discovered with FBH contributing key components to this emerging technology. This includes applications both at low-pressure and under atmospheric conditions. Semiconductor industry relies on the efficient deposition of very thin material layers. In cooperative work with FBH partners, microplasma was found to be an excellent means to advance layer quality and growth speed. Another emerging topic is medical skin treatment that may expedite wound healing or help with neurodermatitis. FBH is part of a research network exploring the biological effects of microplasma and its medical benefits.

New applications aim at matrix formation of multiple microplasma modules to facilitate processing of large areas. Consequently, the overall size of the single plasma module must be minimized. Today, this size is dominated by the microwave power generator which should deliver in the order of 50 W of RF power. Conventional ways of power generation employ either magnetrons or small signal local oscillators (LO) connected to a cascade of multiple power amplifiers. As is depicted in Fig. 1, these concepts occupy a lot of space and are not suitable for integration in a plasma-module. A significant reduction in size and costs, however, can be achieved by employing power oscillators. These circuits combine generation and amplification of the microwave signal in a single circuit of small form-factor. GaN transistors offer an enormous power density and constitute the device of choice for these oscillators.

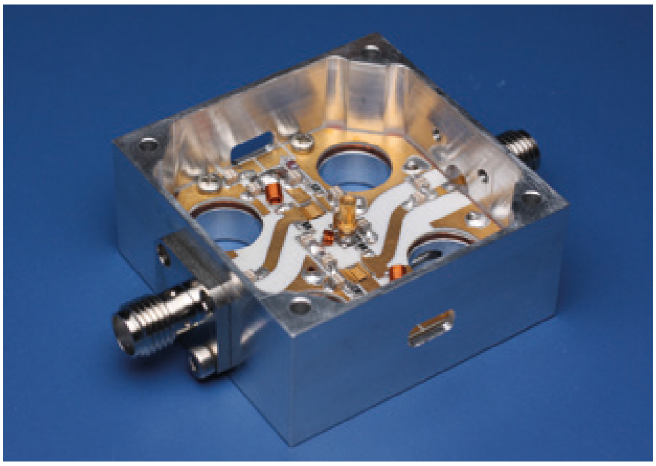


∧ **Fig. 1.** Module size versus output power for different microwave generator concepts.

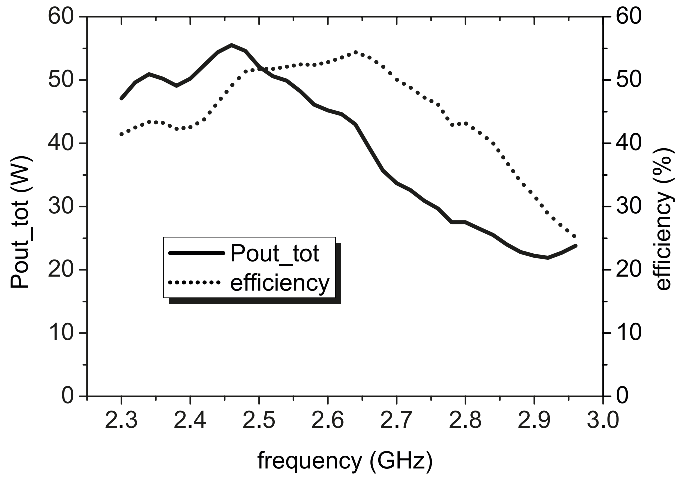


∧ **Fig. 2.** Circuit topology of the differential GaN power oscillator.

Targeting an output power of 50 W and 10 cm² footprint a new type of compact power oscillator has been developed at FBH. It was realized by employing a differential circuit concept (Fig. 2) consisting of a pair of FBH GaN powerbars. Each bar contains five transistor cells with 0.5 micron gate length and is capable of delivering 25 W RF power. With a special feedback network, the transistors are coupled in a way that oscillation at 2.45 GHz and high output power can be achieved simultaneously. The power is delivered to two separate 50 Ω output ports which exhibit a phase shift of 180°. By means of a variable tuning capacitor the oscillation frequency can be adjusted manually.



∧ **Fig. 3.** GaN power oscillator prototype 36 x 36 mm².



∧ **Fig. 4.** Measured total output power and efficiency as a function of oscillation frequency.

The power oscillator prototype shown in Fig. 3 covers a frequency range from 2.3 to 3 GHz. An output power of 50 W is ensured throughout the entire ISM frequency band, providing an efficiency better than 43 %. Peak output power and efficiency is 57 W and 54 %, respectively. The frequency dependent values are depicted in Fig. 4. In terms of phase noise, a state-of-the-art value of -125 dBc/Hz is achieved at 1 MHz offset.

An exact locking of the oscillation frequency is mandatory to comply with frequency regulations under all temperature and supply voltage conditions. This requires electronic tuning of the oscillator. As this feature would also extend the range of applications, future research activities focus on a method to electrically tune the oscillation frequency. This function is standard in the common low-power RF circuits, but has not been demonstrated in microwave power oscillators so far. High-voltage swings are the main reason why classical VCO design methods cannot be employed. Addressing this challenge forms the next step in the development and subject of the ongoing work in the field.

The microwave power oscillator activities were partly funded within the framework Campus PlasmaMed (contract ID 13N11187) by the Federal Ministry of Education and Research.

Mithilfe von Mikroplasma-Quellen können Gase in einem hochkonzentrierten Strahl ionisiert werden. Diese Technologie, die sowohl unter Atmosphärendruck als auch im Niederdruckbereich angewandt wird, ist die Basis für eine Reihe innovativer Anwendungen. Sie reichen von kritischen Prozessschritten in der Halbleiterfertigung bis zu medizinisch-biologischen Applikationen, etwa bei der Hautbehandlung. Neue Entwicklungen im Bereich der Mikroplasmen stützen sich auf Matrixanordnungen vieler solcher Quellen, mit denen auch größere Flächen effizient und gezielt bearbeitet werden können. Dazu werden aber Mikroplasma-Module mit integrierter Leistungserzeugung benötigt; die konventionellen Systeme mit separatem Mikrowellengenerator und Verstärker benötigen zu viel Raum, um sie in einer Matrixanordnung integrieren zu können. Basierend auf der aktuellen GaN-Transistortechnologie ist es dem FBH gelungen, einen kompletten Generator zu entwickeln, der in der Lage ist, 50 W Mikrowellenleistung auf einer Fläche von nur etwa 10 cm² zu erzeugen. Dieser neuartige Leistungsoszillator erzielt eine Effizienz von mehr 43 % im Bereich von 2,3 - 3 GHz. Zukünftig werden damit sehr kompakte Plasmaquellen-Module entstehen, die sich dicht in einer Matrix anordnen lassen und so die Bearbeitung großer Flächen ermöglichen.

Publication

C. Bansleben, W. Heinrich, "Compact High-Power Oscillator With 2.45 GHz Differential Output", 43rd European Microwave Conference (EuMC), Nuremberg, Germany, Oct. 8-10, pp. 818-821 (2013).

For further information:

http://www.fbh-berlin.com/business-areas/microwave-components-systems

http://www.fbh-berlin.com/departments/microwave-department

GaN Electronics
GaN-Elektronik

Business Areas & Research
Geschäftsbereiche & Forschung

Die Schwerpunkte der Arbeiten des Geschäftsbereichs GaN-Elektronik liegen auf Galliumnitrid (GaN)-Bauelementen für Anwendungen in der Mikrowellentechnik und Leistungselektronik. Zu den Aktivitäten gehören die Bauelementkonzeption, die Entwicklung und Optimierung von geeigneten Prozessmodulen sowie deren Integration in einen Gesamtprozess. Sie decken die gesamte Wertschöpfungskette ab: von der Epitaxie bis hin zu fertig montierten, lieferfähigen Bauelementen. Im Rahmen verschiedener strategischer Kooperationen mit industriellen Partnern sorgt das FBH für einen raschen Technologietransfer, unter anderem zur BeMiTec AG (Berlin Microwave Technologies), einem Spin-off des FBHs.

Alle Entwicklungen beruhen auf dem synergetischen Zusammenwirken von Bauelementsimulation, und -design, Epitaxie, Prozesstechnologie und Charakterisierung. Hinzu kommen Lebensdauermessungen und die Analyse potenzieller Ausfallmechanismen. Die Arbeiten erfolgen in Abstimmung mit allen beteiligten Abteilungen und Geschäftsbereichen.

National geförderte Forschungsprojekte und direkte Industrieprojekte unterstützen diese Arbeiten; vermehrt profitiert der Geschäftsbereich von europäischen Förderprogrammen. So koordiniert das FBH jetzt im dritten Jahr das europäische HiPoSwitch-Projekt, eine Themenstellung aus dem Bereich der GaN-Leistungselektronik. Die 2012 begonnenen Entwicklungen von Ka-Band-MMICs zur Realisierung von GaN-Leistungsverstärkern im 30 GHz-Bereich für die weltraumgestützte Kommunikation wurden intensiviert – nicht zuletzt durch die Bewilligung eines weiteren EU-geförderten Forschungsprojekts (GaNSat).

Im Bereich der GaN-Mikrowellenelektronik verfügt das FBH über zwei abrufbare Prozessvarianten: eine zur Realisierung von diskreten GaN-Mikrowellentransistoren für Leistungsverstärker im Bereich des L-, S- und C-Bands in 0,5 µm Gatetechnologie, die andere ermöglicht monolithisch-integrierte Mikrowellenschaltkreise im X- Band basierend auf einem 0,25 µm GaN-MMIC-Prozess. Ein weiterer derartiger Prozess für Schaltkreise im Ka-Band-Bereich mit 0,1 µm Gatelänge wird derzeit entwickelt. Diese GaN-MMIC-Prozesse ermöglichen die Realisierung einer Vielfalt von Schaltungsdesigns, die sowohl aus dem FBH als auch von Projektpartnern kommen und auf Multi-Project-Wafern realisiert werden. Dazu gehören mehrstufige X-Band-Leistungs-MMICs, Schaltverstärker und robuste rauscharme Verstärker. Schnell schaltende, laterale GaN-Schottkydioden mit Schaltzeiten im ps-Bereich erweitern den GaN-MMIC-Prozess; sie werden u.a. für neue Klasse-S-Verstärkerarchitekturen eingesetzt.

Im Bereich der GaN-Leistungselektronik stehen selbstsperrende Schalttransistoren für hohe Sperrspannungen bei gleichzeitig geringen Einschaltwiderständen im Vordergrund der Entwicklungen. Systematische Optimierungen des epitaktischen Aufbaus, der Prozessmodule und der lateralen Strukturen führten zu vielversprechenden, international sehr stark beachteten Ergebnissen. Selbstsperrende GaN-Leistungstransistoren mit über 600 V Sperrspannung, 75 mΩ Einschaltwiderständen und sehr guten Schalteigenschaften wurden mehrfach an Projektpartner für den Aufbau von Demonstratorsystemen geliefert.

Transistoren in quasi-vertikaler Bauweise ermöglichen den Einsatz etablierter Montagetechniken und bieten darüber hinaus das Potenzial zur beidseitigen Entwärmung der Chips. Die dazu notwendigen Prozessmodule wurden im vergangenen Jahr entwickelt und zu einem Gesamtprozess zusammengeführt. Hocheffiziente, schnell schaltende, laterale GaN-Schottkydioden mit Sperrspannungen von über 1000 V runden das Portfolio in diesem Bereich ab.

Die Analyse der Zuverlässigkeit und die Identifikation von Degradationsmechanismen gewinnen bei allen Entwicklungen an Bedeutung und fließen iterativ in die Optimierung des Bauelementprozesses ein. Die Zuverlässigkeitsmessverfahren bestehen aus on-Wafer-Screenings sowie thermisch aktivierten DC- und RF-Langzeittests. Zur Analyse der Ausfallmechanismen besteht zusätzlich eine enge europaweite Kooperation mit verschiedenen Forschungsinstitutionen.

GaN Electronics
GaN-Elektronik

Gallium nitride (GaN) devices for microwave and power electronic applications are the main focus of R&D within the Business Area GaN Electronics. Activities comprise device designs, development and optimization of corresponding process modules, and their integration in a complete process flow. They are covering the full value chain, from epitaxy to completely packaged devices, which are reproducibly available for delivery to customers. To ensure rapid transfer of technology, strategic cooperations with various industrial partners have been established, including the FBH spin-off BeMiTec AG (Berlin Microwave Technologies) that brings GaN prototypes to the market.

Each development is based on the synergetic interaction between physical and thermal device simulation, epitaxy, processing technology, as well as microwave design and characterization. Lifetime measurements and the analyses of potential degradation mechanisms are complementing this work. All activities are realized by intensive interaction with all contributing departments and business areas.

A variety of projects, both nationally and industrially funded, are substantially supporting FBH's R&D work. Additional funding is increasingly coming from collaborative European projects, among them and meanwhile in its third year the HiPoSwitch project. The development of Ka-band MMICs for 30 GHz power amplifiers started in 2012 and is now significantly accelerated due to the acceptance of another European project (GaNSat) targeting at space-borne communication concepts.

To realize discrete and monolithic-integrated microwave devices two basic process versions are available at FBH: one relies on a 0.5 µm GaN technology for discrete L-, S-, and C-band, the other enables X-band GaN MMICs in 0.25 µm gate technology. A further GaN MMIC process targeting Ka-band circuits based on GaN transistors in 0.1 µm gate technology is currently under development. All MMIC processes are forming the technological backbone for a multitude of circuit developments. Designers from both FBH and cooperating partners are placing their circuit ideas on multi-project wafers running on the FBH process line. These include multistage X-band power amplifiers, switchmode amplifiers, and robust low-noise switchmode amplifiers. Fast switching lateral GaN Schottky diodes are being integrated into the current GaN MMIC process in order to cope with the increasing demand for advanced amplifier topologies such as class-S amplifiers.

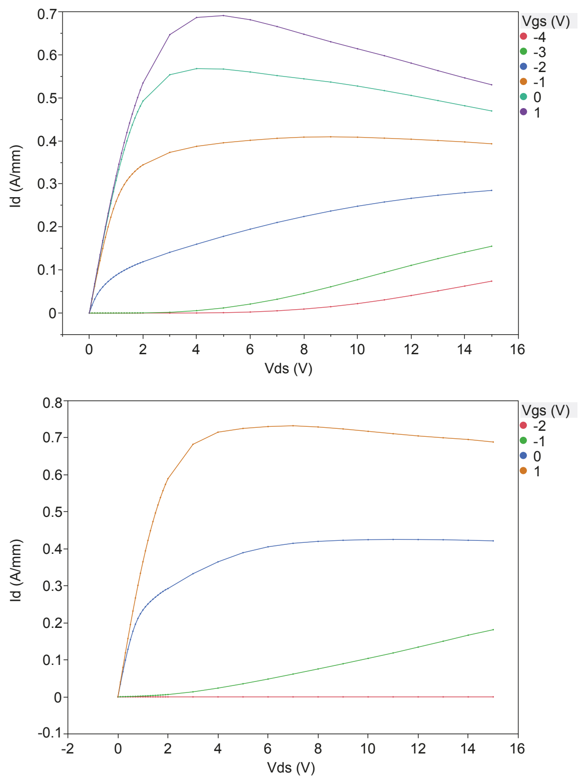
In the field of GaN power electronics, high-voltage normally-off transistors for high blocking voltages, low on-state resistivity, and optimized dynamic properties are dominating the developments. Systematic optimizations of epitaxial design, technological modules, and lateral structure design already led to very promising and internationally highly recognized results. Normally-off GaN power transistors with more than 600 V blocking voltage, 75 mΩ on-state resistance, and good switching capability were delivered to project partners for implementation in demonstrator systems.

Quasi-vertical transistor technologies enable standard chip mounting techniques and additionally offer the potential of dissipating heat from both chip sides. The process modules towards this type of devices have now been developed and are currently being composed to a complete process flow. Highly efficient fast switching lateral GaN Schottky diodes with blocking voltages above 1000 V complement the portfolio.

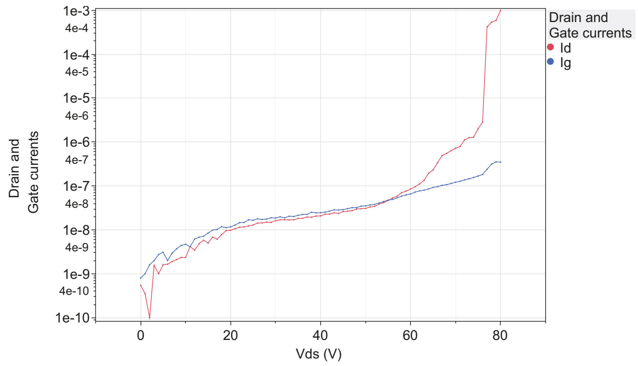
Reliability characterizations combined with the identification of degradation mechanism are increasingly gaining importance and are fed back into technological development cycles. Reliability testing techniques consist of on-wafer screenings and long-term thermally accelerated DC and RF lifetime tests. Moreover, an intensive cooperation with various research institutions in Europe has been established to analyze degradation mechanisms.

Development of 0.1 um GaN HEMTs for co-planar Ka-band MMICs

High throughput satellites (HTS) operating in Ku and Ka bands offer superior bandwidth and power resources and are thus considered as a future topology for satellites. Highly efficient GaN-based solid-state high-power amplifier (SSHPA) MMICs feature high power density and thus smaller size compared to traveling wave tube amplifiers (TWTA). The devices therefore offer new opportunities in satellites by using beam steering and phased array antenna concepts with a multitude of solid-state amplifiers feeding each of the pixel antenna segments. Nevertheless, delivering high power in Ka band from GaN SSHPAs is still a challenge. Currently, only a few companies in the world are offering commercially available GaN high-power amplifiers for Ka-band applications. Most of the problems associated with design and development of mm-wave GaN HEMTs are related to the short gate length required for transistor operation in the given frequency range.



∧ **Fig. 1.** Output characteristics of transistors with 100 nm gate length fabricated with the old (top) and new (bottom) epi-design.



∧ **Fig. 2.** Drain (red line) and gate (blue line) current at pinched-off conditions.

The FBH has developed a new short gate fabrication technology for GaN HEMTs using ICP etching with thermally reflowed ZEP 520A as an etch resist mask. This technology allows realizing dimensions down to 50 nm and sloped sidewall profiles. Recently, it has been improved by replacing manual resist processing operations, such as coating, development, and thermal reflow, by automatic processing. Major intention of this approach is to achieve better reproducibility of gate dimensions. Table 1 shows results of 4-inch wafer processing comparing manual and automatic resist processing. As can be seen, the automatic process provides good wafer-to-wafer reproducibility together with the desired trench size.

Short-channel effects appearing during operation of HEMTs with deep submicron gate lengths impose strict limitations on the heterostructure design and subsequently on the maximum output current of these transistors. An example for the influence of short-channel effects on the transistor properties is depicted in Fig. 1 top. It shows output characteristics of transistors fabricated during gate module development, using 100 nm gates and a standard epi-structure with AlGaN barrier thickness t_{bar} = 18 nm. These devices could not be turned off anymore at a high drain voltage – a problem related to the short-channel effect that very well agrees with literature data for an L_G/t_{bar} aspect ratio less than 5. Due to large gate-channel separation and a small gate length, current modulation is significantly compromised leading to punch-through. To avoid effects like this, a new epi-design with t_{bar} = 12 nm has been developed in order to provide an L_G/t_{bar} aspect ratio of more than 8. A thin AlGaN barrier with a comparatively high Al concentration of 32 % was placed on top of an AlGaN buffer structure with a 4 % Al concentration. This provides a good confinement of electrons in the channel and thus widely avoids short-channel effects (Fig. 1 bottom).

Breakdown voltage measurements performed on a wafer with the newly developed epi-design showed a mean breakdown voltage value of 75 V, indicating that the problem with preliminary breakdown has been solved. Fig. 2 shows the reverse bias I/V characteristics of a fully pinched transistor. At around 75 V the drain current starts to rise, followed by a steep gate current increase. This indicates an onset of punch-through at this voltage. The new epitaxial design has shifted this punch-trough effect to a voltage range such that it is not critical anymore for the targeted device operation voltage of

wafer no.	gate processing	trench size after development (nm)	trench size after resist reflow (nm)	trench size after etching (nm)
1	manual	170	65	110
2	automatic	165	61	105
3	automatic	161	66	105
4	automatic	162	66	105

< **Table 1.** Gate trench dimensions after different process steps using manual and automatic resist processing.

25 V. In order to achieve even higher breakdown voltages, the L_G/t_{bar} aspect ratio should be increased either by reducing AlGaN barrier thickness, with subsequent reduction of transistor maximum current, or by increasing gate length, with subsequent decreasing of maximum operation frequency.

In conclusion, the newly developed technology of embedded gate GaN HEMT fabrication using resist thermal reflow and highly anisotropic ICP etching has been modified for fully automatic resist processing. It has then been successfully implemented in FBH's technological process of Ka-band transistor fabrication. Results of first 4-inch wafers processing showed good gate size uniformity over the wafer and wafer-to-wafer repeatability. The standard epi-design used for gate module development has been modified by reducing the barrier thickness from 18 to 12 nm. The subsequent increase of the L_G/t_{bar} aspect ratio from 5 to 8 avoids possible short-channel effects during transistor operation. After modifying the epi-design, short-channel effects that have appeared on experimental wafers were successfully eliminated, and breakdown voltage was increased up to 75 V.

The support from the European Community in the frame of the project GaNSat (contract no. 606981) is gratefully acknowledged.

Das FBH hat den GaN-MMIC-Prozess für das Ka-Band in Bezug auf die 0,1 µm Gatestrukturierung weiterentwickelt und ein neues Epitaxiedesign eingeführt. Im lithografischen Teil der Arbeiten wurde ein Lack-Reflow-Prozess in Verbindung mit hoch anisotropem ICP-Ätzen implementiert. Dieser wurde erfolgreich in den technologischen Prozess zur Fertigung von Ka-Band-MMICs integriert. Ergebnisse der ersten 4-Zoll-Wafer zeigen eine gute Uniformität der Gatedimensionen über den Wafer und von Wafer zu Wafer. Im Epitaxiedesign wurde die Dicke der AlGaN-Barriere von 18 auf 12 nm reduziert und somit das Verhältnis zwischen Gatelänge und Kanaldicke von 5 auf 8 gesteigert. Damit konnten Kurzkanaleffekte erfolgreich verhindert werden und die Durchbruchspannungsfestigkeit auf über 75 V erhöht werden. Damit sind jetzt Ka-Band-MMICs mit einer Betriebsspannung von ca. 25 V möglich.

Publications

K.Y. Osipov, S.A. Chevtchenko, O. Bengtsson, P. Kurpas, F. Brunner, N. Kemf, J. Würfl, "Implementation of slanted sidewall gates technology in the fabrication of S-, X-, and Ka-band AlGaN/GaN HEMTs", CS Mantech Conf., accepted for publication (2014).

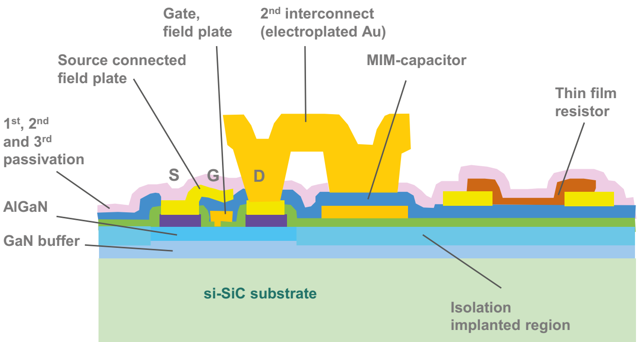
K.Y. Osipov, W. John, N. Kemf, S.A. Chevtchenko, P. Kurpas, M. Matalla, O. Krüger, J. Würfl, "Comparison of different methods for GaN HEMTs gate fabrication", WOCSDICE (2013).

K.Y. Osipov, W. John, N. Kemf, S.A. Chevtchenko, P. Kurpas, M. Matalla, O. Krüger, J. Würfl, "Fabrication technology of GaN/AlGaN HEMT slanted sidewall gates using thermally reflowed ZEP resist and CHF_3/SF_6 plasma etching", CS Mantech Conf. (2013).

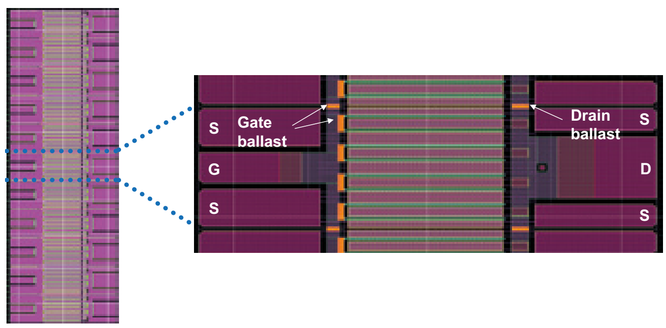
GaN power bars robust against high VSWR stress

In many applications, power transistors in solid-state power amplifiers are facing very high reflections at the output. These power reflections are caused by a non-perfect 50 Ω load to the amplifier output. This may have several reasons. It can be accidentally caused by a missing connection between the amplifier and the successive system; in antenna-based systems it can be induced by ground testing, nearby objects, or out-of-band RF power entering the system. Reflections can cause damage to the final stage transistors, for example by large voltage swings, leading to voltage breakdown, or by large power dissipation, evoking thermal wear-out.

The usual way of protecting a power amplifier in a system is to use a ferrite-based isolator between the amplifier and the succeeding antenna. This isolator will direct all reflections to a 50 Ω load resistor and, as a result, the amplifier always sees a 50 Ω load impedance. However, isolators are bulky components limiting further integration and miniaturization of solid-state power amplifiers. Therefore, a VSWR (voltage standing wave ratio) rugged transistor that survives high output reflections is needed. To develop such transistors and solid-state-based protection circuitry were goals of the recently terminated GaN-Isolator project at FBH. The project, financed by ESA and conducted in co-operation with TNO Netherlands, aimed at providing GaN based solid-state solutions to replace the traditional ferrites in space system.



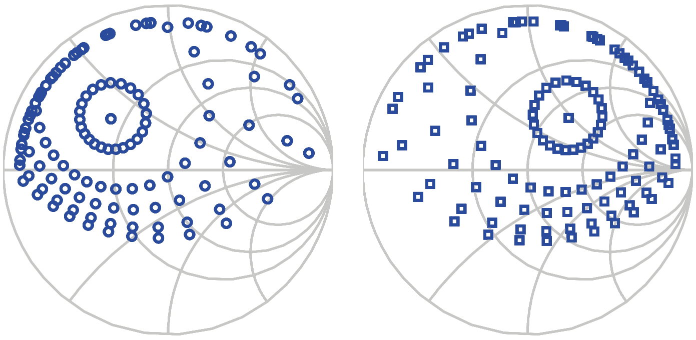
∧ **Fig. 1.** Cross section of the present FBH GaN-HEMT technology for the fabrication of power bars (0.5 µm gate technology) and X-band MMICs (0.25 µm gate technology).



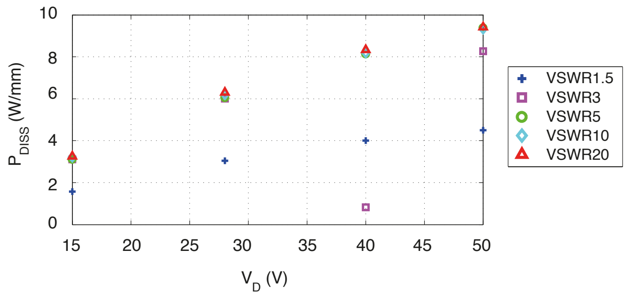
∧ **Fig. 2.** Layout of the 11-cell power-bar (l.); detailed layout of a 8-finger cell with integrated gate and drain ballasting resistors to prevent odd-mode oscillations (detail, r.).

Due to their high breakdown voltage levels combined with short-term high-temperature operation capabilities, GaN devices can be built very robust. At FBH, several measures have been taken to maintain these qualities and to further enhance the technology for operation under high VSWR conditions. A novel epi-design, delivering the requested power level at the targeted bias without excessive power density, has been implemented by reducing the Al concentration in the barrier. In addition, a thicker AlGaN layer was chosen to avoid extreme high field regions at the drain side edge of the gate in order to prevent reliability problems. This design has immensely improved the thermal budget for higher voltage operation (e.g. 50 V). Source-connected field plates as seen in Fig. 1 have also been introduced to spread out high electric fields at the drain side edge of the gate and to reduce the probability of electron trapping in these regions.

For the devices targeting high-power applications, in this case 11-cell transistors with 22 mm total gate width, the stability of the devices and particularly the prevention of so-called odd mode oscillations has been improved. In this regard, monolithically integrated ballasting resistors connected between the cells on gate and drain terminals as shown in Fig. 2 have been very effective. Furthermore, series gate resistors are an additional option to reduce gain and thereby to further improve stability.



∧ **Fig. 3.** VSWR mapping of test devices operated at 15 V (l.) and 50 V (r.), showing increasing levels of VSWR stress of 1.5, 3, 5, 10 and 20 (counted from the point of optimum power match).



∧ **Fig. 4.** Example of maximum dissipated power for each VSWR level.

Novel measurement procedures have also been developed to investigate the performance and boundary conditions of GaN technology when exposed to high VSWR stress on the output. These procedures aim at answering questions like: What level of stress can GaN components handle for how long? What kind of VSWR stress is damaging for the device? What is the physical mechanism for damage creation (e.g. is it caused by a field effect or a purely thermal issue).

Various levels of VSWR were automatically tested and the performance, before, during, and after stress was investigated. The VSWR tests were conducted in load-pull setups with increasing levels of VSWR originating from VSWR, 1:1 equivalent to matching for maximum output power (P_{out}). Fig. 3 shows VSWR test patterns obtained from a single transistor cell for different drain bias conditions (15 V and 50 V). Different levels of VSWR stress bring the device to different phase positions and thus create different levels of thermal and field stress, as can be seen in Fig. 4. Based on the full VSWR investigation it has been concluded that the FBH technology is very robust against VSWR stress and experiences only temporary changes when exposed to high VSWR levels for time periods in the 1 - 5 s range. Of course, extreme VSWR levels at high supply voltage creates very high levels of power dissipation (up to 9 W/mm according to Fig. 4) and can therefore lead to permanent performance degradation.

The authors gratefully acknowledge the support from the European Space Agency (ESA) under contract no. 21854/08/NL/GLC.

Häufig kommt es beim Einsatz von Hochfrequenz-Leistungsverstärkern am Ausgang zu einem hohen Stehwellenverhältnis (VSWR). Dies kann etwa beim Einbau des Verstärkers oder bei Bodentests von Satellitenradaranlagen passieren. Durch diese Fehlanpassung entsteht am Ausgang des Leistungstransistors, abhängig von der Phase der Reflexion, entweder eine hohe Feldstärke oder eine hohe thermische Belastung. GaN-HEMTs haben materialbedingt eine sehr hohe Festigkeit gegenüber Fehlanpassungen, d. h. eine gute VSWR-Robustheit. Wegen der hohen GaN-Durchbruchspannung kommt es nicht zu Spannungsüberschlägen. Aufgrund der guten Wärmeleitfähigkeit des SiC-Substrates wird die zusätzliche Verlustwärme gut abgeführt. In einigen Anwendungen muss man trotzdem die Robustheit noch verbessern. Durch verbesserte Messmethoden, optimierte Transistoren und schnelle Schutzschaltungen ist es in einem ESA-Projekt gelungen, einen gegenüber hohen Stehwellen unempfindlichen 100 W GaN-Leistungsverstärker zu entwickeln. Die Arbeiten haben zudem gezeigt, dass Leistungsverstärker durch schnelle Schaltungen gut gegenüber hohem VSWR geschützt werden können. Die Wirkung der VSWR-Belastung kann dadurch weiter verringert werden.

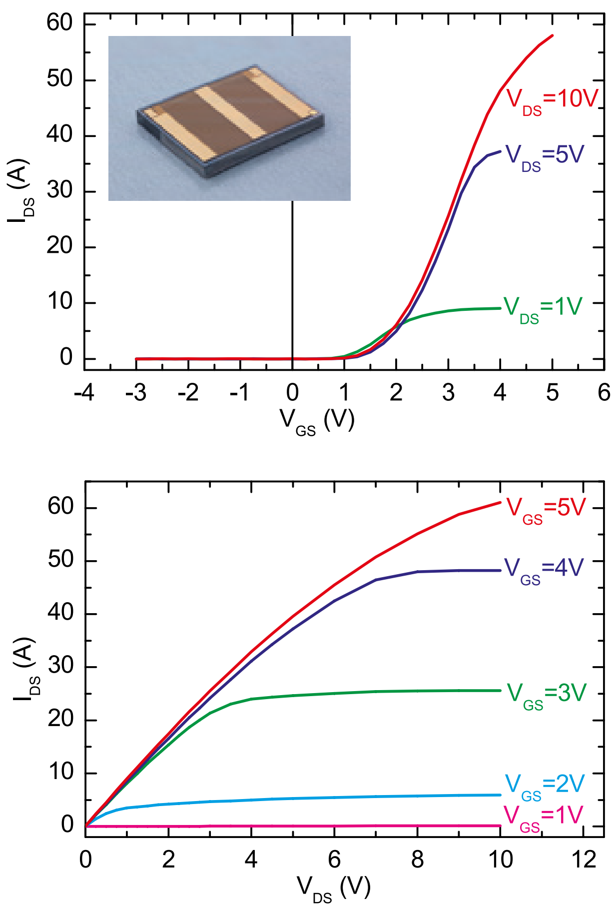
Publication

O. Bengtsson, S.A. Chevtchenko, A. Chowdhary, W. Heinrich, J. Würfl, “VSWR Testing of RF-Power GaN Transistors”, accepted for publication at the European Microwave Week (2014).

65 mΩ normally-off high-voltage switching transistors for efficient energy conversion

High-voltage GaN-based power switching transistors enable efficient power converters with increased power density. High converter switching frequencies can be realized with lateral GaN-based HFETs due the low area-specific on-state resistance for a given blocking strength and the low gate charge required for switching. Lateral GaN HEMTs have intrinsic normally-on properties since the transistor gate needs to be negatively biased to deplete the transistor channel. However, a normally-off characteristic is required for power electronics application because of inherent power-system safety requirements and the preferred unipolar gate driver design.

At FBH, a p-type doped GaN stripe was introduced as transistor gate to convert the GaN HEMT into a normally-off device. This gate module suppresses the drain current at 0 V gate bias to 100 nA/mm or less. It allows for 400 - 500 mA/mm drain current in the device on-state at 5 - 6 V gate bias. The 5 V gate swing is larger than for conventional GaN HEMTs with a Schottky-type metal gate and enables secure on-state and off-state conditions even in applications with high EMI noise. Static and dynamic electrical device characterization has been performed for a transistor with 134 mm gate width, featuring a chip size of 2.9 x 3.8 mm². The device has +1 V threshold voltage, 60 A pulse current, 100 mΩ on-state resistance and 600 V blocking voltage.

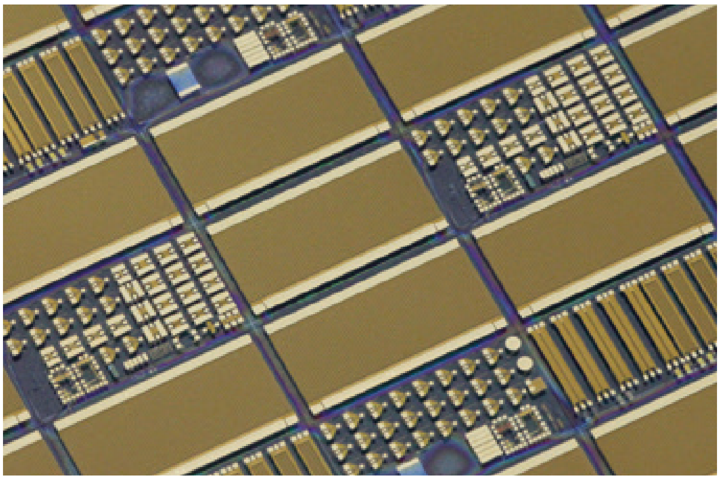


∧ **Fig. 1.** Transfer characteristics (top) and output characteristics (bottom) of a normally-off 100 mΩ/600 V GaN switching transistor with 134 mm gate width. Inset: 2.9 x 3.8 mm² transistor chip.

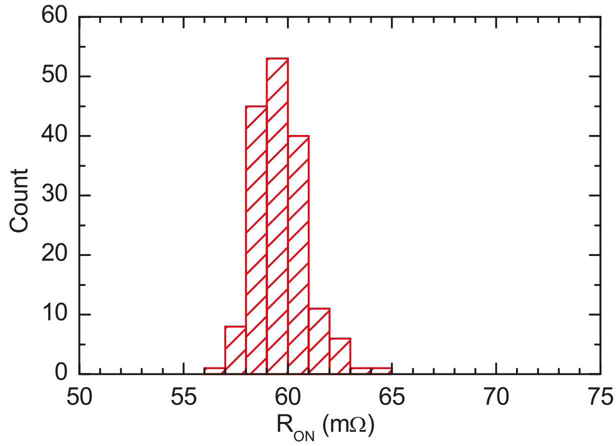
The drain-source switching energy for this device for 400 V switching is 4 µJ and thus only 60 % of a similarly rated Si-based CoolMOS super-junction transistor. The required gate charge for switching was measured as Q_G = 5.5 nC. The resulting benchmark of Q_G x R_{ON} = 0.55 nCΩ is a factor 5 - 10 smaller than for Si-based MOSFETs with the same voltage rating. The targeted benefit in switching efficiency is thus proven for the FBH GaN-switching transistor technology.

New 600 V devices have been fabricated using a new layout that was optimized for more efficiently using the semiconductor area. 214.4 mm gate width was arranged on a 4.4 x 2.3 mm² chip. These devices show very low on-state resistances of 65 mΩ or less. The area-specific on-state resistance was thus decreased by 40 % from R_{ON} x A = 1.09 Ωmm² to R_{ON} x A = 0.66 Ωmm². Less chip area is required for this FBH GaN transistor as compared to similarly rated 600 V Si-based super junction MOSFETs, featuring typically R_{ON} x A = 1 - 3 Ωmm². This example demonstrates that efficient use of the chip area is also possible for the lateral design of GaN transistors. Actually, it can compete with the vertical design of Si-based transistors.

Support from EU FP7 project HipoSwitch (Grant no. 287602) is gratefully acknowledged.



∧ **Fig. 2.** 65 mΩ/600 V GaN switching transistors (4.4 x 2.3 mm²) with 214.4 mm gate width on a 3" wafer. Smaller test structures are also visible.



∧ **Fig. 3.** Wafer distribution of the transistor on-state resistance, R_{ON}.

Für Anwendungen in der Leistungselektronik hat das FBH selbstsperrende 100 mΩ/600 V GaN-Schalttransistoren mit 60 A Pulsbelastbarkeit realisiert. Die Einsatzspannung liegt bei 1 V, und die hohe Aussteuerbarkeit des Gates bis 5 V erlaubt zuverlässiges Schalten in Systemumgebungen mit hoher elektromagnetischer Interferenz. Die Drain-Source-Schaltverluste für 400 V Schalten liegen bei 4 µJ und betragen damit nur 60% der Schaltverluste eines Si-basierten CoolMOS-Transistors. Die für das Schalten nötige Gateladung beträgt 5,5 nC. Sie ist damit um Faktor 5 - 10 kleiner als für vergleichbare Si-basierte MOSFETs. Somit ist eine signifikante Reduzierung der Schaltverluste durch GaN-basierte Schalter für diese selbstsperrenden GaN-Transistoren belegt. In einer neuen Designiteration mit selbstsperrenden 65 mΩ/600 V Transistoren wurde der flächenspezifische Einschaltwiderstand zudem von R_{ON} x A = 1,09 Ωmm² auf R_{ON} x A = 0,66 Ωmm² reduziert. Damit benötigen die GaN-Schalter weniger Chipfläche als vergleichbare Si-basierte 600 V Super-Junction-MOSFETs, die typischerweise ein R_{ON} x A = 1 - 3 Ωmm² aufweisen.

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N. Badawi, O. Hilt, E. Bahat-Treidel, S. Dieckerhoff, J. Würfl, "Switching Characteristics of 200 V Normally-off GaN HEMTs", Int. Exhibition and Conf. for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (PCIM Europe), Nuremberg, ISBN 978-3-8007-3505-1, pp. 319-324, (2013).

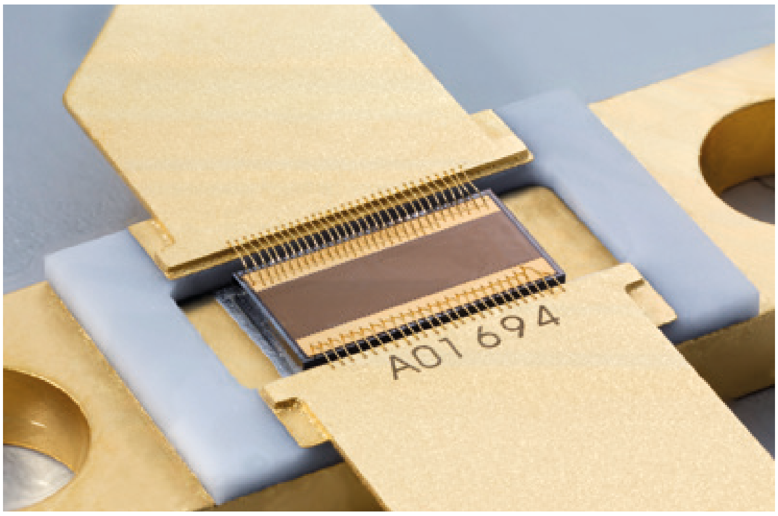
Fast switching GaN Schottky diodes

GaN high-voltage switching Schottky diodes are of particular interest for low-loss free-wheeling diodes combined with efficient GaN-based high-voltage transistor switches for power conversion. In terms of switching speed they outperform Si- and SiC-based Schottky diodes at given high-voltage capability. The same technology applied for smaller designs is, of course, even suited for large-signal microwave switching applications.

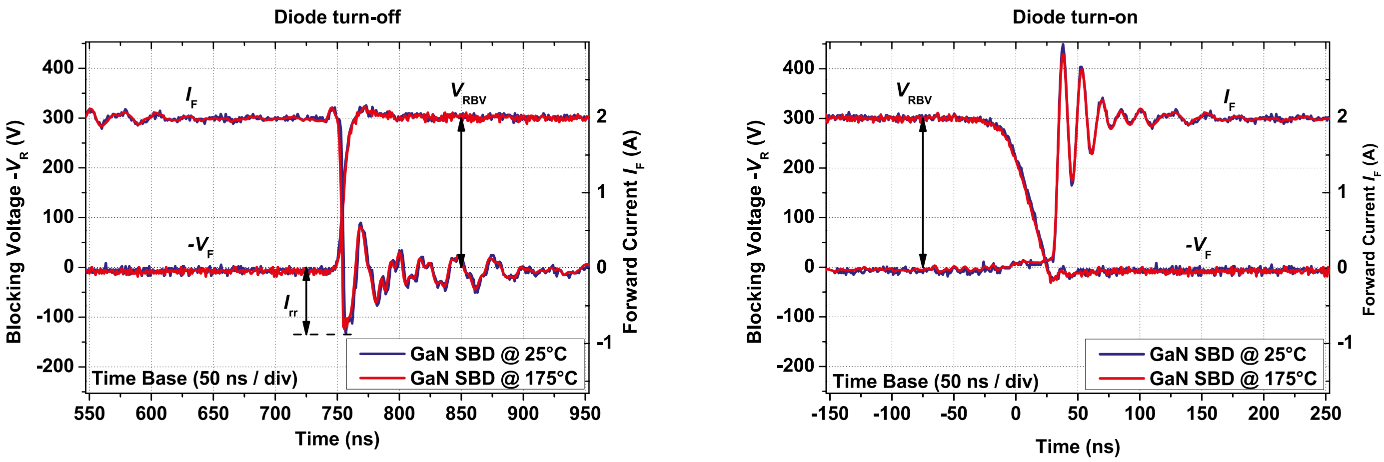
In general, on-state conduction and switching losses as well as reverse bias leakage significantly limit the power switching performance of Schottky barrier diodes (SBD). GaN-based heterostructure SBDs are capable to shift these limitations and thus enable highly performing diodes in terms of low conduction and low switching losses. These properties are due to efficiently exploiting the two-dimensional electron gas (2DEG) located at the heterojunction between GaN and AlGaN epitaxial layers. This region is characterized by high sheet carrier density and high mobility in the channel associated with high breakdown field strength.

A new generation of lateral diodes has been developed and manufactured with 134 mm channel width and a die size of 4.4 x 2.3 mm^2 (shown in Fig. 1). These diodes have a resistance of 100 mΩ at a forward operation bias, which is matched to the GaN-based power transistors also manufactured at the FBH. In forward bias the diodes are characterized by an onset bias of 0.6 V and an absolute resistance of 280 mΩ , measured at a forward current of 6 A. Characterization of the diodes at elevated temperature shows that these devices feature a high zero-temperature crossover point (ZTCP) at 2.2 A (!). This is much above their onset voltage, which allows for nearly temperature-compensated diode operation in this bias point. At 175°C the diodes are characterized by an onset bias of 0.4 V and an absolute resistance of 320 mΩ . In reverse characteristics the new design with 134 mm wide diodes show blocking beyond 1000 V. The leakage current of such a large area device at a reverse bias of 600 V is lower than 4 mA (i.e., lower than 30 µA/mm).

Recent GaN-based 2 A/600 V Schottky diode switching characterizations conducted at the Technische Universität Berlin show a switch-off time of less than 20 ns while switching 2 A/530 V. In a newly designed measurement set-up the diodes have been switched at a switching rate of 1.5 MHz using 200 mΩ/400 V FBH GaN transistors. The diodes are switching 2 A and 300 V in the temperature range between 25°C and 175°C (shown in Fig. 2). They demonstrate very fast switching times of ~10 ns for the voltage transients and ~6 ns for the current transients with transient slops of 30 V/ns and 0.36 A/ns. From transient analysis the capacitive charge Q_{rr} of the GaN diode has been estimated at 5.5 nC and 5.7 nC for 25°C and 175°C respectively. Since GaN Schottky diodes are majority carrier devices there is no reverse recovery charge. However, they still show some reverse recovery effect due to the parasitic capacitance of the Schottky diode.



< **Fig. 1.** A lateral 6 A/600 V GaN SBD in a demonstration package.



∧ **Fig. 2.** FBH SBD waveform at 1.5 MHz, reverse blocking voltage V_{RB} = 300 V, forward current I_F = 2 A at temperatures T = 25°C and 175°C (W = 25 mm, L_{ac} = 15 µm), using a FBH GaN-HEMT 400 V/12 A as active switch (measured at TU Berlin).

A similar technology of recessed Schottky diodes has been successfully incorporated in FBH´s baseline X-band GaN-HEMT MMIC fabrication. Since a moderate breakdown voltage in the range of 150…180 V for microwave applications was anticipated, the focus was on minimized diode capacitance for high-speed operation. In fact, a fast switching time of 24 ps was determined for GaN Schottky diodes with 0.25 mm anode width, suitable for monolithic integration with GaN-HEMTs in novel switched-mode-type power amplifiers. Furthermore, larger GaN Schottky diodes with 12 mm anode width were delivered to the European Space Agency (ESA) for development of highly efficient DC/DC converters. In a benchmarking of diodes from different sources performed at ESA, FBH´s devices revealed the lowest capacitance at a given current and voltage rating.

Support from the Federal Ministry of Education and Research (LES project PowerGaN-Plus, contract no. 13N10908) is gratefully acknowledged.

Für Anwendungen in der Leistungselektronik sind GaN-Schottky-Dioden als verlustarme Bauelemente von besonderem Interesse. Kombiniert mit effizienten GaN-Schalttransistoren werden sie als Freilaufdioden in Inverterschaltungen eingesetzt. Für diesen Zweck wurde eine neue Generation lateraler Schottky-Dioden mit 134 mm Kanalweite und einer Chipgröße von 4,4 x 2,3 mm² entwickelt. Diese Dioden weisen in Flussrichtung einen Widerstand von 100 mΩ bei einer Einsatzspannung von 0,6 V auf. Messungen des Schaltverhaltens, die an der TU Berlin durchgeführt wurden, ergaben eine Ausschaltzeit kleiner als 20 ns beim Schalten eines 2 A/530 V-Pulses. Ferner können die Dioden im Temperaturbereich zwischen 25°C und 175°C einen hohen Strom schalten, sie erreichen dabei Spannungstransienten von 30 V/ns. Eine analoge Technologie, jedoch mit viel kleinerer Diodenperipherie, kann auch für Schaltverstärker im Mikrowellenbereich genutzt werden. Entsprechende Schottky-Dioden wurden als monolithisch-integrierte Komponente des 0,25 µm X-Band-MMIC-Prozesses an die Europäische Weltraumagentur zur Evaluierung neuartiger Konzepte von hocheffizienten Mikrowellen-Leistungsverstärkern geliefert.

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For further information:

http://www.fbh-berlin.com/business-areas/gan-electronics

Diode lasers
Diodenlaser

Business Areas & Research
Geschäftsbereiche & Forschung

Das Ferdinand-Braun-Institut ist weltweit führend bei der Erforschung und Entwicklung der Chiptechnologie für hochbrillante Diodenlaser vom roten bis zum nah-infraroten Spektralbereich (630 nm...1180 nm). Der zunehmende Einfluss der optischen Technologien in Industrie und Forschung führt dazu, dass die Zahl der Anwendungen weiter steigt und damit auch die Forschungsaufgaben für das Institut. Für Industriepartner wurden unter anderem im vergangenen Jahr Chips mit spezieller, nahezu runder Abstrahlcharakteristik entwickelt, und Simulationen legten die Grundlagen für neuartige Chips für LIDAR-Anwendungen. Die langfristig angelegten Arbeiten zur Effizienz- und Brillanz-Steigerung von Diodenlasern laufen planmäßig weiter, wobei der nächste Integrationsschritt, die Entwicklung von anwendungsorientierten Laserstrahlquellen, zunehmend an Bedeutung gewinnt.

Mit seinen Kompetenzen deckt das FBH den gesamten Teil der Wertschöpfungskette ab: von Simulation und Entwurf über die technologische Realisierung der Halbleiterchips bis zum Aufbau einsatzfähiger Diodenlasermodule. Besondere Schwerpunkte der Arbeiten im Jahr 2013 lagen auf dem Gebiet der Chiptechnologie in der Entwicklung einer E-Beam-basierten, stabilen Technologie zur Erzeugung von Oberflächengittern und deren Einsatz für hochbrillante DBR- und DFB-Diodenlaser, ebenso wie auf leistungsstarken Diodenlasern, die im Wellenlängenbereich 1100 nm...1200 nm entwickelt wurden. Darüber hinaus wurde die Modultechnologie für weltraumqualifizierbare Laserstrahlquellen und für Anwendungen in der Materialanalyse (Raman- und Fluoreszenzspektroskopie) weiter vorangetrieben.

Herausragende Ergebnisse des Jahres 2013 waren:

- *Monolithische Diodenlaser für die Materialbearbeitung, die in fünf mit ~2 nm Abstand gestuften, stabilisierten Wellenlängen abstrahlen,*
- *Entwicklung einer E-Beam-basierten Technologie für DFB-Laser mit Oberflächengitter,*
- *Demonstration einer hybriden Diodenlaserstrahlquelle für den gelben Spektralbereich auf der Basis von hochbrillanten 1120 nm Diodenlasern,*
- *Entwicklung und Erprobung von stabilen 2-Wellenlängen-Strahlquellen bei 785 nm für miniaturisierte Optoden in der Ramanspektroskopie (SERDS),*
- *Diodenlaser mit sehr geringer Divergenz und maßgeschneidertem, nahezu rundem Strahlprofil für den Einsatz in externen Resonatoren.*

Diode lasers
Diodenlaser

The Ferdinand-Braun-Institut is one of the world-leading research centers for the chip technology of high-brilliance diode lasers, covering the wavelength range from 630 nm to 1180 nm. The ever-increasing influence of optical technologies in industry and research leads to a rising amount of applications, subsequently also increasing R&D work at the institute. For industrial partners, for example, chips with special, almost round beam characteristics have been developed, and simulations were laying the foundation for novel chips suitable for LIDAR applications. It is a matter of course that the FBH also kept track of its long-term development objective to constantly increase efficiency and brilliance of diode lasers, observing, at the same time, an upward trend on application-oriented laser sources.

Capabilities of the FBH cover the full value chain, from simulation, design, and technological realization of semiconductor chips to the assembly of ready-to-use diode laser modules. The focus regarding chip technology in 2013 was on developing an E-beam-based, stable technology to generate surface gratings used in high-brilliance DBR and DFB diode lasers. Also, powerful and capable diode lasers have been developed for the wavelength range 1100 nm…1200 nm. A further focus has been on the module technology for space-qualified laser sources and applications in materials analytics, such as Raman and fluorescence spectroscopy.

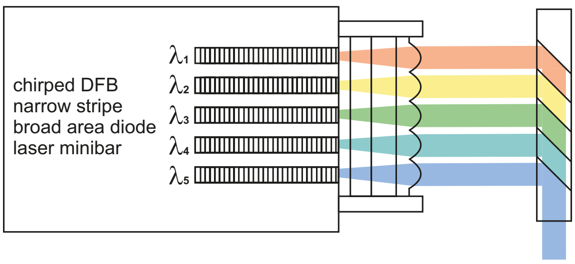
Outstanding results in 2013:
- Monolithic diode lasers for materials processing, emitting in five stabilized wavelengths that are arranged at ~2 nm distance from each other,
- Development of an E-beam-based technology for DFB lasers with surface gratings,
- Demonstration of a hybrid diode laser source for the yellow spectral region, based on high-brilliance 1120 nm diode lasers,
- Development and testing of stable 2-wavelength beam sources at 785 nm that are integrated in miniaturized optodes used for Raman spectroscopy (SERDS),
- Diode lasers with very low divergence and tailored, almost round beam profile for use in external resonators.

New design for high-order surface gratings enables spectrally stabilized DFB diode laser arrays for next-generation high-power laser systems

Over the past decades the laser has become a crucial tool for materials processing. In industrial applications such as sheet metal cutting lasers have replaced mechanical and chemical tools completely, due to the higher processing speed, precision, efficiency, and reliability. As well as high power (> 2 KW) and high efficiency, these applications require a small beam parameter product (BPP) < 10 mm-mrad. Therefore, this market is increasingly dominated by diode-pumped solid-state and fiber lasers which convert the lower BPP of high-power diode lasers and diode laser bars into nearly diffraction-limited laser light. High-power diode laser systems combine the emission of many broad area (BA) diode lasers, while the BPP increases with the number of single emitters. These diode laser systems are preferred for many applications due to their high efficiency and low cost, but are not yet able to serve applications that require low BPP.

Laser systems based on spectral beam combining (SBC) of external stabilized broad-area (BA) diode lasers are promising candidates for improving the BPP at high powers. In these systems, each BA laser is spectrally stabilized using external feedback, operating with a unique wavelength and narrow spectral width. The emission is then combined into a single beam via spectrally selective elements (e.g. gratings) so that the BPP of the whole system approaches that of a single emitter. There are two key limitations to this approach. First, external spectral stabilization adds cost, increases size and set-up complexity, and is a reliability hazard. Second, the system is limited to the BPP of the single emitters used which is typically BPP = 3…4 mm-mrad for commercial BA lasers, hampered principally by the lateral (in-plane) properties.

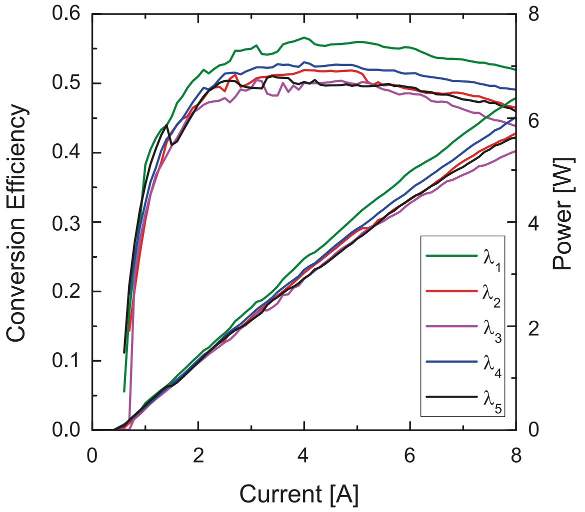
To overcome these limitations, the FBH is developing high-power, high-efficiency single emitters with a reduced BPP which are monolithically spectrally stabilized within the EU project BRIDLE (www.bridle.eu). For increased system brightness and optimal fiber-coupling the diode lasers should operate with reduced BPP (< 2 mm-mrad) and small vertical far field angle (95% power content), VFF95 < 40°. The resulting diode lasers are fabricated as mini-bars for reduced assembly costs. Monolithic spectral stabilization is integrated into the mini-bar, using high-order Bragg gratings that are etched directly into the wafer surface after epitaxy. These gratings are particularly attractive for SBC as these can be fabricated using I-line stepper lithography and reactive ion etching (RIE), enabling the grating period and hence emission wavelength of neighboring emitters to be freely varied, with each laser stripe lasing at a different wavelength. In this way, each emitter can be directed into a single fiber via low-cost dielectric filters, as schematically shown in Fig. 1.



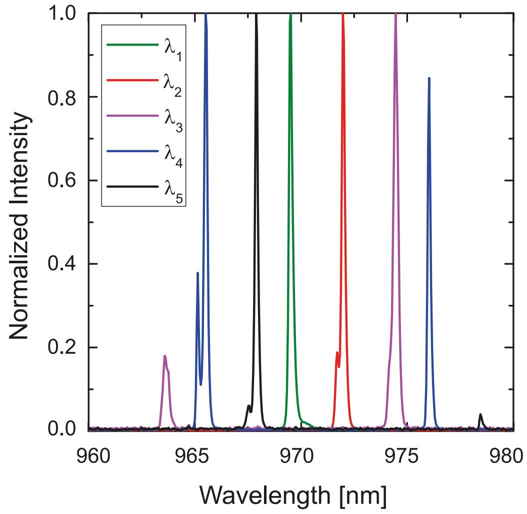
∧ **Fig. 1.** Schematic drawing of dense SBC of monolithically wavelength-stabilized mini-bars with dielectric filters, as targeted within the BRIDLE project.

Distributed-feedback narrow-stripe broad-area (DFB-NBA) lasers are particularly promising candidates for these SBC systems. NBA lasers with W = 40 µm that are spectrally stabilized using distributed Bragg reflectors (DBR) as a rear facet reflector have previously been shown to be promising single mode sources up to P ~ 0.5 W. However, the development of spectrally stabilized NBA lasers for high efficiencies to P > 5 W has not been reported to date.

Now, it has been shown that DFB-NBA single emitters with 30 µm stripe width successfully cut off higher-order lateral modes, improving BPP. The use of uniform, surface-etched, 80th-order Bragg gratings with weak coupling strength enables the DFB-NBA laser to operate with high efficiency. Currently, such sources operate with > 50% efficiency at output power, P > 6 W with a VFF95 < 40°. The emission wavelength



∧ **Fig. 2.** Efficiency and optical output power of five DFB-NBA lasers with chirped central wavelengths at heatsink temperature of 20°C.



∧ **Fig. 3.** Spectra of five DFB-NBA lasers with chirped central wavelengths at an optical output power of 5 W at heatsink temperature of 20°C.

is stabilized at about 970 nm and the spectral width is < 0.7 nm (95 % power) at P = 6 W. The in-plane BPP < 1.8 mm-mrad is half that of a DFB-BA lasers with W = 90 µm.

Next-generation mini-bars for dense SBC will be constructed within the BRIDLE program. They will be composed of five DFB-NBA single emitters, with slightly chirped grating periods, and thus chirped central wavelengths. Their anticipated performance can be extrapolated from the light current characteristics of single emitters, as shown in Fig. 2. At P > 5 W every emitter operates with a conversion efficiency > 45 %. When dense SBC is applied to these emitters, a power of up to 30 W with the beam quality of a single emitter should be achieved. The spectral properties of the emitters at P = 5 W are shown in Fig. 3. Good spectral stabilization and narrow bandwidth < 1 nm of every emitter is achieved. However, lasing occurs not only in 80^{th}-Bragg order, but also in adjacent 81^{th}-Bragg order, depending on the detuning between Bragg wavelength and the thermally shifting gain maximum. In ongoing studies the FBH is pursuing mini-bars with further improved conversion efficiency, power, and suppressed spectral side modes.

This work was funded by the European Commission within the BRIDLE project (part of the Seventh Framework Programme) under grant number 314719.

Laser mit Ausgangsleistungen im kW-Bereich spielen eine immer wichtigere Rolle in der Materialbearbeitung. Die Kernkomponente solcher Lasersysteme besteht aus einer Vielzahl von Diodenlasern. Deren Strahlung wird räumlich gebündelt, um sie direkt oder als Pumpquelle für Faser- oder Festkörperlaser zu nutzen – je nach erforderlicher Strahlqualität. Im EU-Projekt BRIDLE erarbeitet das FBH gemeinsam mit Partnern die Grundlagen für eine deutlich effizientere Bündelung auf der Basis von spektralen Multiplexen. Das FBH designt, prozessiert und charakterisiert dafür Chips (Laserbarren), auf denen jeweils fünf Emitter mit stabilisierten Wellenlängen im Abstand von 2 nm platziert sind. Sie liefern bis zu 30 W Ausgangsleistung und, durch Überlagerung der Wellenlängen, eine Strahlqualität vergleichbar mit Einzelemittern. Diese Chips mit monolithisch integrierter Wellenlängenstabilisierung bilden die Basis für ein 2 kW-Lasersystem. Für den Wellenlängenmix und dessen Stabilisierung setzt das FBH eine neuartige Gittertechnologie ein. Damit konnten pro Emitter Leistungen > 6 W, eine spektrale Breite von 0,7 nm und < 2 mm-mrad Strahlqualität mit einem elektro-optischen Wirkungsgrad > 50 % erreicht werden.

Publications

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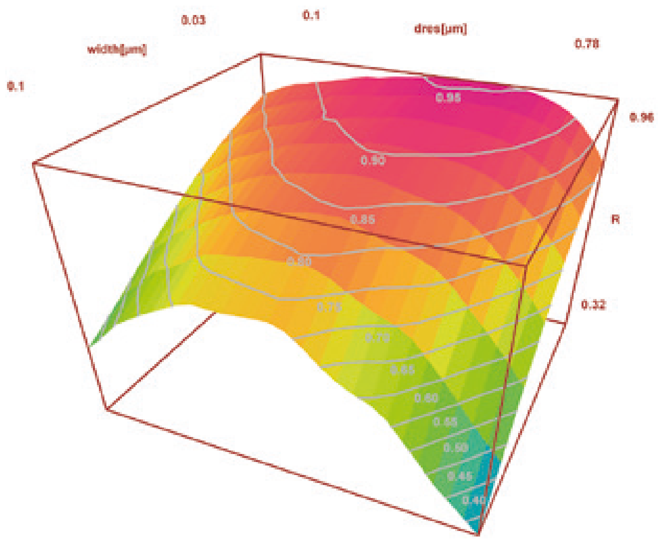
P. Crump, G. Erbert, H. Wenzel, C. Frevert, C.M. Schultz, K.-H. Hasler, R. Staske, B. Sumpf, A. Maaßdorf, F. Bugge, S. Knigge, G. Tränkle, "Efficient High-Power Laser Diodes", IEEE Journal Selected Topics in Quantum Electronics, vol. 19, no. 4, pp. 1501211, (2013).

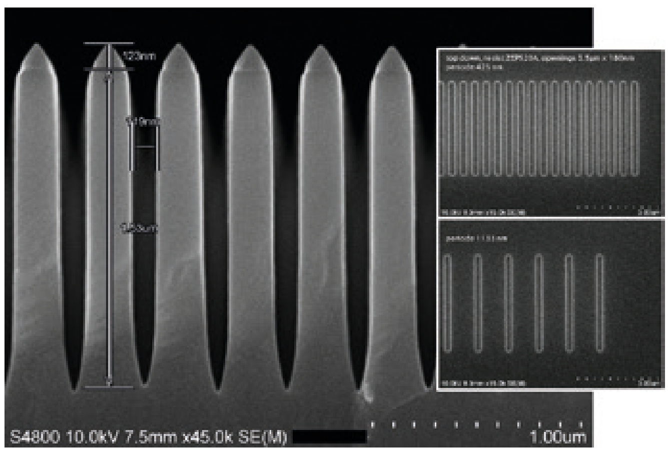
Surface grating technology – basic developments for a production technology for highly brilliant diode lasers

The improvement of laser diode brilliance requires not only enhancing their beam quality, but also reducing their spectral widths. Bragg gratings that are integrated in the resonator are cost-efficient elements and do effectively reduce the spectral widths from a few nanometers down to the femtometer scale. Furthermore, wavelengths are stabilized over a distinct current and temperature range. In this way, semiconductor lasers become attractive for narrow-band applications such as pumping of atomic clocks and spectroscopy. Wavelengths division multiplexing (WDM) of several emitters is accessible, allowing novel sensor applications as well as power scalability for direct material processing. The laser technology group at FBH develops the corresponding technologies for laser diode fabrication, including integration of Bragg gratings into edge-emitting devices. Studies regarding the impact of grating design and processing on optoelectronic laser characteristics are performed. Efforts aim not only at obtaining record performances of laser diodes, but also at providing a stable and reliable grating production technology.

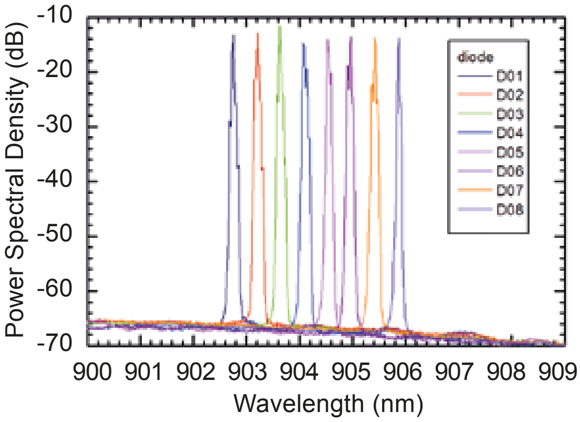
Current work concentrates on improving surface gratings, since the additional effort of this technological approach is relatively low. In order to define highly reflective Bragg gratings, periodical grooves with defined depth, shape, and period have to be introduced into the laser surface. It has been theoretically shown with the mode-matching tool CAMFR that highly reflective gratings require high duty cycles of the periodic structures. Structure sizes below 100 nm (Fig. 1) have to be implemented in the waveguide region, which guides high optical intensities. In earlier work, these gratings were defined by using i-line stepper lithography. Due to the limited resolution, grating periods could only be defined down to 720 nm. Reasonable reflectivities of high-order gratings were obtained by etching V-shaped grooves that are tapered towards the active region, providing the required high duty cycle. Electron-beam lithography (VISTEC SB251) allows fabricating structures with significantly smaller dimensions down to a 240 nm period. Simulations predict an increase of the maximum grating reflectivity and of the process tolerances. Depending on the vertical structure,



∧ **Fig. 1.** 3D contour plot of the maximum reflectivity of a 1 mm long 3[th] order Bragg grating versus the width of the grooves at the bottom and the residual layer thickness d_{res}.



∧ **Fig. 2.** SEM pictures: cross section of a surface grating defined with electron-beam lithography. Insets: SEM top down pictures of opened ZEP520A resist.



∧ **Fig. 3.** Optical spectra of eight ridge waveguide DBR emitters placed on a 6 mm wide bar.

reflectivities of more than 90% are possible if d_{res} – distance between the ground of the grating groove and the active region – is properly adjusted.

The technology developed includes three steps – electron-beam lithography, etch mask, and etching of the grating grooves. Each technological step has been separately optimized. The grating production starts with the deposition of a multi-level etch mask system (750 nm hard baked AZ nLOF and a 50 nm Ti layer). A 300 nm thick ZEP resist is then spun on top of the hard mask and patterned with electron-beam lithography. Proximity correction of the electron-beam data is applied, allowing controllable > 100 nm wide grating openings for different waveguide dimensions (small ridge waveguides) and different grating periods (insets Fig. 2). After defining the grating structure the Ti layer is opened. Ti then serves as etch mask for the underlying AZ nLOF, which is selectively patterned with an O_2 plasma. In order to exactly control depth and shape of the grating grooves, the influence of several reactive ion-etching (RIE) parameters has been investigated. Besides gas species, flow ratio, RF power, and pressure the etching selectivity and rate have been optimized. A deeper understanding of the micro loading effect – which mainly causes a strong dependence between sizes of the resist openings and etch rate – was necessary to exactly control the grating etch process, which is able to produce up to 1.5 µm deep gratings (Fig. 2).

This process was successfully applied to produce different types of semiconductor lasers with integrated gratings, such as DBR, tapered DBR, and high-order DFB lasers. Fig. 3 shows, as an example, the optical spectra of eight DBR lasers with surface gratings placed on a 6 mm wide bar. The difference of the periods of the third order gratings is 0.22 nm between the neighboring emitters, resulting in 0.45 nm spectral distances. Further, it has been demonstrated that the resulting low order Bragg gratings show increased reflectivities compared to higher order gratings and result in enhanced wall-plug efficiencies of DBR lasers. The electron-beam process offers improved flexibility and reproducibility and is applicable on AlGaAs and AlGaAs/AlGaInP vertical laser structures. It can therefore be applied for the whole spectrum of active GaAs-based optoelectronic devices.

Mithilfe von Bragg-Gittern, die in den Halbleiterlaserresonator integriert werden, kann die Ausgangswellenlänge stabilisiert und die emittierte Linienbreite reduziert werden. Diese verbesserten spektralen Eigenschaften machen Halbleiterlaser für eine Vielzahl von Anwendungen in der Metrologie und Spektroskopie interessant. Zudem lässt sich damit das emittierte Licht von Lasern mit zueinander leicht verstimmten Ausgangswellenlängen (wavelengths division multiplexing, WDM) überlagern. Dieses Verfahren erlaubt es, neben neuen spektroskopischen Anwendungen, Halbleiterlaser für die direkte Materialbearbeitung einzusetzen. Am FBH werden die zugehörigen Lasertechnologien zur Prozessierung von Halbleiterlasern und der Gitterintegration entwickelt. Neben der Herstellung von Lasern mit höchster Brillanz gilt dabei der Stabilisierung der Gitterprozesse ein besonderes Augenmerk. Gegenwärtige Arbeiten konzentrieren sich auf die Integration von Oberflächengittern mittels Elektronenstrahl-Lithografie und die Optimierung von Ätzmaskentechnologie und trockenchemischen Ätzverfahren.

Publication

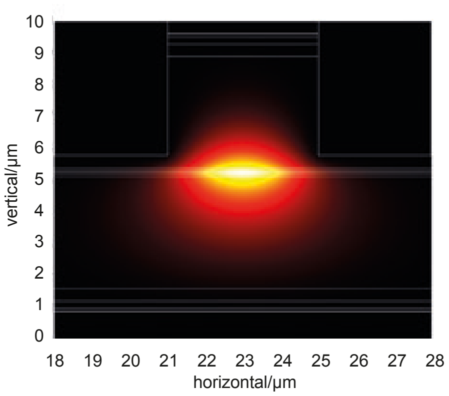
J. Fricke, A. Klehr, O. Brox, W. John, A. Ginolas, P. Ressel, L. Weixelbaum, G. Erbert, "Y-branch coupled DFB-lasers based on high-order Bragg gratings for wavelength stabilization", Semicond. Sci. Technol., vol. 28. no. 035009 (2013).

Diode lasers with a circular beam divergence for robust coupling in compact hybrid-integrated laser light sources

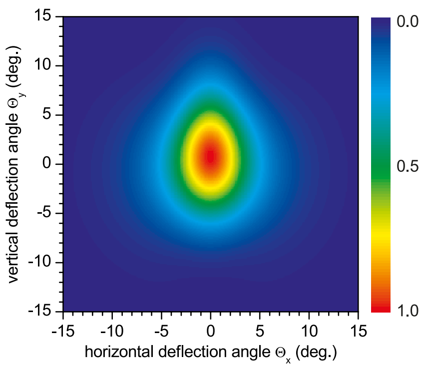
Diode lasers must often be combined with other optical components to meet the requirements given by applications like coherent optical communication, second harmonic generation, and atomic spectroscopy. These components include power amplifiers, modulators, crystals for non-linear frequency conversion, and external resonators. In order to realize modules as compact as possible, coupling of the laser beam into the optical components is realized by several micro lenses, thus collimating and focusing the beam. However, adjustment and gluing of the lenses require a precision in the sub-µm range and are very time-consuming. Particularly compact and low-cost modules have been realized by butt coupling of the laser and the optical component without any lenses between them. For efficient coupling, the beam emitted by the diode laser must match the field guided by the optical component as much as possible. Some components like external resonators require a laser beam with low divergence and symmetric profile, i.e., circular cross section.

However, the beam emitted by a common ridge-waveguide (RW) laser has typically a highly asymmetric profile due to the large vertical divergence. The ratio of the vertical and horizontal (or lateral) divergence angles of the beam, the beam ellipticity, can reach values up to 5. In order to cut down ellipticity, the vertical divergence must be reduced while maintaining the lateral divergence and the beam quality. This can be accomplished by using extremely thick optical confinement layers and quantum barriers. These barriers feature low refractive indices reducing the waveguiding effect of the multi-quantum active region. Additionally, width and height of the ridge waveguide governing the lateral divergence can be optimized.

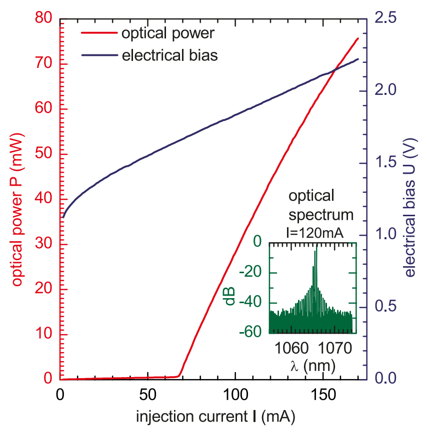
For the design of a corresponding RW laser emitting at a wavelength around 1064 nm, we used a commercial software package to solve Maxwell equations in two dimensions. Thereby, the optical modes have been calculated considering only the distribution of the refractive indices given by the deposited layers and etched trenches, neglecting the impact of electronic and thermal effects for simplicity reasons. Fig. 1 exhibits the calculated intensity of the fundamental mode of an optimized design. The regions with differing refractive indices are separated by straight light lines. The RW structure can be clearly identified.



∧ **Fig. 1.** Calculated distribution of the intensity of the fundamental mode (vanishing intensity = black, highest intensity = light, the light straight lines separate regions with different refractive indices).



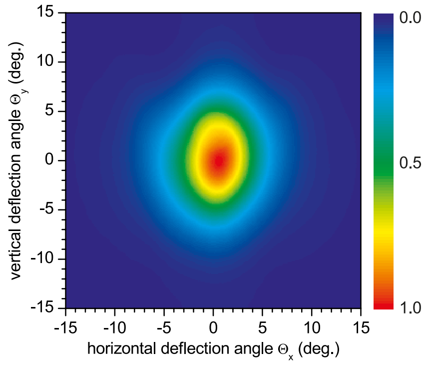
∧ **Fig. 2.** Calculated distribution of the intensity of the fundamental mode in the far field (vanishing intensity = blue, highest intensity = red).



∧ **Fig. 3.** Electro-optical characteristics of the fabricated RW laser measured in continuous-wave operation at a heat-sink temperature of 25°C.

parameter	simulation	measurement
horizontal angle (FWHM)	6.8°	6.8°
vertical angle (FWHM)	10.1°	9.8°
ellipticity (FWHMs)	1.5	1.4
horizontal 1/e2 angle	13.6°	13.7°
vertical 1/e2 angle	17.2°	16.8°
ellipticity (1/e2 angles)	1.3	1.2

∧ **Table 1.** Comparison of simulated and measured beam divergence angles and ellipticities.



∧ **Fig. 4.** Intensity distribution of the lasing mode in the far field measured at a power of 40 mW (vanishing intensity = blue, highest intensity = red).

The spatial extension in both horizontal and vertical direction is nearly equal. The intensity distribution of the emitted beam in dependence on the deflection angles, i.e., the far-field distribution, is shown in Fig. 2 as a pseudo-color plot. The cross-section is close to circular, with ellipticities of 1.5 and 1.3 calculated from the vertical and horizontal divergence angles at half of the maximum intensity (FWHM) and at the $1/e^2$ intensity level, respectively, as listed in table 1.

Wafers with the optimized layer design were grown by metal-organic vapor phase epitaxy (MOVPE) and then processed to RW lasers. Devices with 400 µm cavity length and rear as well as front facet reflectivities of 95% and 30%, respectively, were mounted epi-side up on heat sinks. They were then experimentally characterized in continuous-wave (CW) operation at a heat sink temperature of 25°C. The dependence of optical power and electrical bias on the injected current is shown in Fig. 3. The threshold current is 70 mA, and the slope of the power-current characteristics is 0.8 W/A. These values are quite reasonable with regard to the intended small beam divergence. At a current of 170 mA an output power of 76 mW is reached. The inset of Fig. 3 shows an optical spectrum recorded at a current of 120 mA, with a peak wavelength at 1066 nm.

Fig. 4 depicts the far-field distribution measured with a goniometer, exhibiting very good agreement with the simulated distribution. The ellipticities of 1.4 and 1.2 (FWHM and $1/e^2$ level, respectively) determined from the experimental divergence angles given in table 1 are even a little bit smaller than the theoretical values. Thus, it can be concluded, that the FBH succeeded to develop a ridge-waveguide laser with a near-circular extremely narrow beam divergence which enables simple low-cost coupling into optical components.

Um den Anforderungen spezieller Anwendungen gerecht zu werden, müssen Diodenlaser oft mit anderen optischen Komponenten wie etwa Kristallen kombiniert werden. Zur Strahlformung werden in kompakten Modulen Mikrolinsen eingesetzt. Deren Justage und Klebung erfordert eine Präzision im Sub-Mikrometerbereich und ist daher sehr zeitaufwändig. Damit der Laserstrahl einfacher und robuster gekoppelt werden kann, muss er möglichst direkt kompatibel mit den optischen Eigenschaften der optischen Komponenten sein. Der Laserstrahl sollte zudem über einen kreisförmigen Querschnitt verfügen. Typischerweise ist dieser jedoch in der vertikalen Richtung stark divergent, woraus ein elliptisches Profil resultiert. Am FBH ist es gelungen, einen Laser auf der Basis einer Rippenwellenleiter-Struktur zu entwickeln, der bei 1064 nm Wellenlänge mit einer nahezu kreisförmigen Abstrahlcharakteristik emittiert. Trotz der geringen Strahldivergenzen von 17° und 14° in der vertikalen bzw. horizontalen Richtung beträgt der Schwellenstrom nur moderate 70 mA, der Anstieg der Leistungs-Strom-Kennlinie liegt bei immerhin 0,8 W/A.

Publication

A. Pietrzak, H. Wenzel, P. Crump, F. Bugge, J. Fricke, M. Spreemann, G. Erbert, G. Tränkle, "1060-nm ridge waveguide lasers based on extremely wide waveguides for 1.3-W continuous-wave emission into a single mode with FWHM divergence angle of 9° x 6°", IEEE J. Quantum Electron., vol. 48, no. 5, pp. 568-587, (2012).

Highly brilliant laser sources – yellow light in medicine and bio-analytics

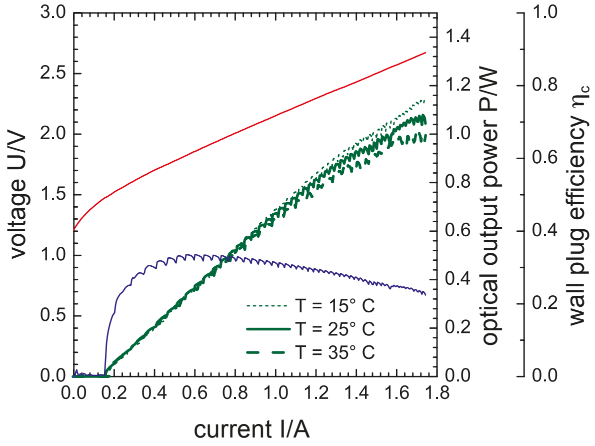
Laser sources emitting light at 560 nm are key components for a wide range of applications in medicine, environmental analytics, and precision atomic spectroscopy. These include time-resolved fluorescence spectroscopy, confocal microscopy, photocoagulation in ophthalmology, medical skin treatments, DNA sequencing, high-resolution refractometry, and flow cytometry. However, currently available laser sources based on fiber and solid-state lasers lack direct modulation capability, suffer from low efficiency, and are usually fixed in their wavelength.

Semiconductor-based laser sources developed within the BMBF-funded Yellow project provide solutions to eliminate these restrictions. The approach bases upon a highly brilliant monolithic diode laser source and subsequent frequency doubling (SHG) with the help of small crystal. This process sustains and even improves beam quality and spectral properties. The diode laser sources make rapid modulation possible. Semiconductor chip and the crystal for SHG can be mounted together with the necessary micro-optical elements in a matchbox-sized housing. Due to the compact dimensions these modules also enable mobile applications. Therefore, examinations can be executed in-situ, and results are thus available much faster.

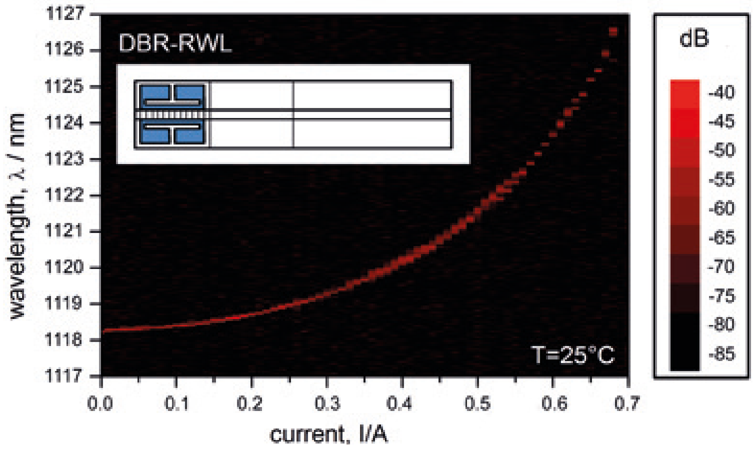
The key components developed at the FBH are monolithic diode lasers emitting at 1120 nm with integrated distributed Bragg reflectors. In a first step, ridge-waveguide diode lasers (DBR-RWL) have been developed. These lasers feature highly strained InGaAs quantum wells and 5th order surface grating Bragg reflectors, ensuring a stabilized emission wavelength. The technology of integrating a Bragg grating into the rear part of an RW has been adopted from previously developed DBR-RWLs emitting at 1064 nm. The challenge now was to combine the active region of existing quantum well laser structures exhibiting reliable laser emission near 1120 nm with cladding layers suitable to accommodate DBR surface gratings. Furthermore, the new structure comprises electrical heaters next to the DBR grating, which enable a fine tuning of the emission wavelength via temperature (see inset Fig. 3).

Fig. 1 depicts a DBR-RWL on C-mount. These tunable and highly brilliant DBR-RWLs achieved output powers up to 1 W at 1.7 A and a maximum conversion efficiency of about 34 % with a spatial and spectral single-mode emission. The plot of Fig. 2 shows typical

< Fig. 1. DBR-RWL on C-mount with contact for DBR heaters.



∧ **Fig. 2.** Voltage, optical power and efficiency as a function of driving current of a DBR-RWL at 1120 nm.



∧ **Fig. 3.** Map of the spectral distribution of a DBR-RWL as a function of current through the DBR heater section. Inset: sketch of the chip layout with DBR heater (blue).

power-voltage-current characteristics of a DBR-RW laser at heat sink temperatures of 15, 25, and 35°C in CW operation. The wavelength can be tuned via the resistive heater over more than 8 nm or 2000 GHz (Fig. 3). In a preliminary reliability test at 0.4 W a life-time of more than 1,000 h has been demonstrated.

Due to their high brilliance, tunability, and compactness, these monolithic laser diode devices enable non-linear frequency conversion. We achieved an output power of more than 80 mW in the yellow spectral range at 560 nm. Currently, the module development is under way.

This work is funded by the German Federal Ministry of Education and Research in the frame of the InnoProfile-Transfer joint research project “YELLOW” under contract No. 03IPT613Y.

Laserquellen, die bei einer Wellenlänge von 560 nm emittieren, werden in der Medizin und bei umweltanalytischen Messverfahren genutzt. Bei vielen derartigen Anwendungen reichen jedoch Effizienz, Modulationsgeschwindigkeit oder Durchstimmbarkeit der derzeitigen Laserquellen nicht aus. Abhilfe könnten miniaturisierte, halbleiterbasierte Laserquellen schaffen, die derzeit am FBH entwickelt werden. Dank ihres kompakten Aufbaus ermöglichen sie zudem, dass Geräte transportabel werden und Untersuchungen vor Ort durchgeführt werden können. Da direkt emittierende Laserdioden bei 560 nm derzeit noch nicht verfügbar sind, nutzt das FBH das Prinzip der Frequenzverdopplung. Hierzu wurden Rippenwellenleiterdioden bei 1120 nm entwickelt, die auf InGaAs-Quantengräben mit integrierten Oberflächengittern basieren. Diese zeichnen sich durch eine hohe Ausgangsleistung von bis zu 1 W bei beugungsbegrenzter sowie spektral schmalbandiger Emission aus. Damit sind diese Laser ideal für die direkte Frequenzverdopplung geeignet. Dies demonstrieren erste Ergebnisse: Leistungen von mehr als 80 mW nach Frequenzverdoppelung wurden im gelben Spektralbereich erreicht.

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Measuring the frequency noise of free-running diode lasers – a prerequisite for precision spectroscopy

Low frequency-noise semiconductor lasers find application in a variety of fields like atomic physics and coherent optical communication. Some of these applications require an emission linewidth in the kHz or sub-kHz range, others even call for a relative phase stabilization between two lasers. To this end, active frequency stabilization is needed; the optimization of which necessitates characterizing the laser's spectral instability in detail. Therefore, accurately quantifying the frequency-noise power spectral density (PSD) is crucial to develop frequency-stable lasers.

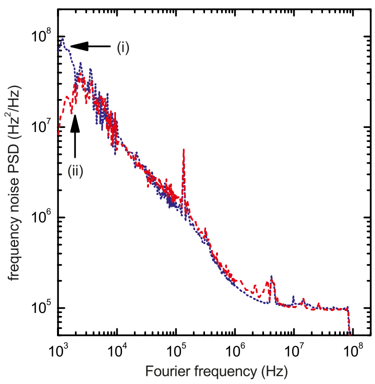
Various methods exist for determining the frequency-noise power spectrum of a laser. Some directly convert the optical signal by using frequency discriminators operating in the optical domain, such as Fabry-Pérot etalons or atomic transitions. Others rely on creating a beat-note signal with a second laser close in frequency to down-convert the optical signal to a beat-note signal in the RF domain. Thus, RF spectrum analysis methods and corresponding equipment can be applied. Unfortunately, the applicability of these approaches is quite limited. Using frequency discriminators can lead to bandwidth limitations imposed by the finite bandwidth of the discriminator. It can even be necessary to use active frequency stabilization to the discriminator, which would alter the frequency-noise PSD. On the other hand, when using RF spectrum analyzers, frequency drifts on the time scale of the measurement pose serious problems.

To overcome these limitations, we selected a different approach that relies on capturing the beat-note signal in the time domain. Data are then post-processed to derive frequency-noise spectra or RF-power spectra (Fig. 2 and 3, respectively). The measurement principle is sketched in Fig. 4. The IQ (in-phase/quadrature) data measured with an RF analyzer is used to access the signal's phase (a). The average angular frequency of the signal is determined, and the corresponding phase evolution is subtracted from the base-band signal phase (b). The corresponding phase-noise PSD is estimated via fast Fourier transform (FFT) (c) and converted to a frequency-noise PSD (d).This method does not require frequency locking of the lasers to each other. Frequency drifts that correspond to frequency modulations on time scales larger than data capture length are efficiently suppressed by the data analysis algorithms. Our method hence avoids problems related to the alternative methods described above.

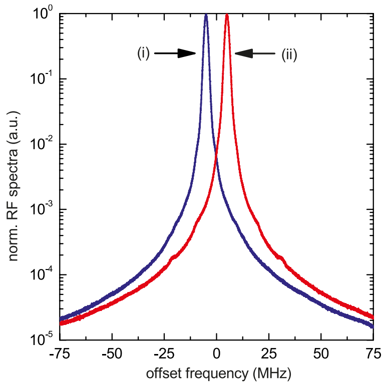
∧ **Fig. 1.** FBH applies hybrid integration technologies to micro-integrate complex optical setups.

To investigate the effect of frequency drifts for our method we simulated various linear frequency drifts superimposed on white frequency noise and chose a Hann window for finite-impulse-response (FIR) filtering. Our simulations provided an upper limit to the acceptable frequency drift rate. Assuming a laser with a noise floor of 10^5 Hz^2/Hz and 10 ms measurement time leads to a maximum acceptable drift rate of 500 MHz/s. Applying adequate temperature stabilization and using low-noise injection current controllers, diode laser drift rates can be kept below this limit. Hence, corruption of frequency-noise PSD spectra by linear frequency drifts of the free-running (diode) lasers can easily be avoided.

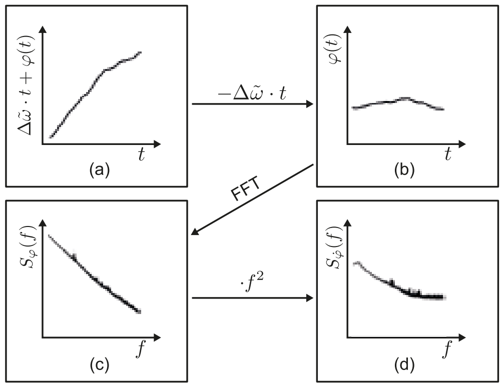
To demonstrate the capability of our method we implemented the algorithm and performed heterodyne beat-note measurements between two DFB diode lasers (@ 780 nm). In the following, we



∧ **Fig. 2.** Frequency-noise PSD measurement with two lasers (frequency difference of 1 GHz): (i) free running, (ii) frequency stabilized.



∧ **Fig. 3.** RF power spectra derived from the same data sets as used for Fig. 2 for (i) free running and (ii) frequency stabilized lasers. Curves were shifted by -5 MHz and +5 MHz, respectively.



∧ **Fig. 4.** Measurement principle.

compare measurements from (i) both lasers free running with (ii) one of the lasers frequency-stabilized to the other to reduce relative frequency drifts. The corresponding frequency-noise and RF spectra are shown in Fig. 2 and 3, respectively. Above 10 MHz, one can clearly observe the white noise floor in Fig. 2. The steep roll-off above 80 MHz reflects the finite IF bandwidth of the RF spectrum analyzer. The curve (ii) reveals the influence of frequency stabilization (frequency noise is suppressed at Fourier frequencies below 3 kHz).

To ensure the validity of the measurement at low Fourier frequencies we estimated the linear frequency drift present in the measurement that lead to Fig. 2 (i). This yielded 105 MHz/s (@ 10 ms), which is well below the 500 MHz/s maximum acceptable drift rate calculated according to our simulations.

In conclusion, we developed a simple method to derive the frequency-noise power spectra from beat-note measurements between two free-running (diode) lasers. The measurement comprises the following steps: digitization of the beat-note signal and subsequent down-conversion to a complex base-band, extraction of the phase as a function of time, subtraction of the linear phase evolution, appropriate filtering, and FFT of the time-dependent phase.

This work was supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant numbers DLR 50WM1132, DLR 50WM1134, DLR 50WM1141, and DLR 50WM1240.

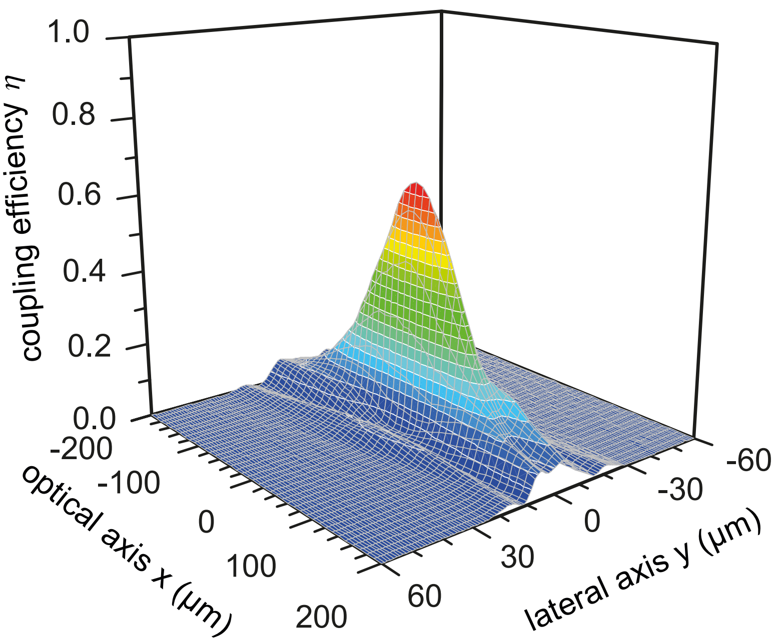
Halbleiterlaser mit geringem Frequenzrauschen werden in der Atomphysik und bei der kohärenten optischen Kommunikation eingesetzt. Häufig ist dabei eine Frequenzstabilisierung nötig, die zu implementieren wiederum detaillierte Kenntnis des Frequenzrauschens verlangt. Daher ist die Bestimmung der spektralen Leistungsdichte (PSD) des Frequenzrauschens eine zentrale Voraussetzung, um frequenzstabile Laser zu entwickeln. Verschiedene Methoden existieren bereits, mit denen sich die PSD von Lasern bestimmen lässt. Allerdings sind viele Ansätze nur begrenzt anwendbar. Deshalb wurde am FBH ein einfaches Verfahren zur Bestimmung der Frequenzrauschspektren freilaufender (Dioden)-Laser entwickelt und getestet. Es basiert auf der Schwebungsmessung zwischen zwei Lasern und umfasst folgende Schritte: Digitalisieren des Schwebungssignals und Heruntermischen ins komplexe Basisband, Ermittlung der Phase als Funktion der Zeit, Subtraktion der linearen Phasenentwicklung, Filterung und Fourier-Transformation der zeitabhängigen Phase.

Improving the applicability of highly brilliant, tapered diode lasers – multiple watt optical power after coupling into a single-mode fiber

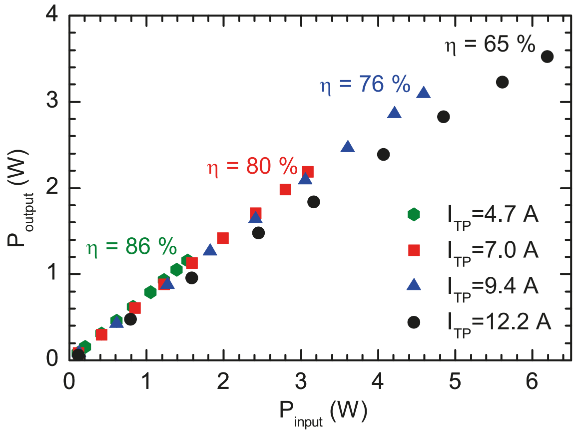
Efficient high-power lasers emitting near-infrared single-frequency radiation in a spatially fundamental mode are highly demanded. They are attractive for applications like pumping of sophisticated solid-state and fiber lasers as well as for frequency conversion. In this context, tapered diode lasers are particularly interesting due to their compactness and low manufacturing costs. The FBH has developed such tapered lasers delivering 10 W output power in continuous-wave (CW) operation. However, the beam of this laser type is characterized by a large astigmatism and a moderate beam quality. In addition, the beam properties change slightly in dependence on the operation current. Therefore, the use of such devices is typically challenging, and often a scientist or an engineer is necessary to operate such laterally tapered diode lasers.

The Ferdinand-Braun-Institut develops compact modules with light output through a fiber, thus enabling simpler handling of tapered diode lasers. The corresponding efforts focus on low-order mode fibers and even single-mode fiber (SMF) coupling to maintain the brightness of tapered diode lasers. The scope of experiments comprises investigations regarding the coupling efficiency into optical fibers in dependence on spatial laser beam properties. A further emphasis is on investigating the tolerances of the optical scheme to maintain a high level of coupling efficiency (Fig. 1). Furthermore, the spatial and spectral properties of the laser radiation behind the optical fiber are determined.

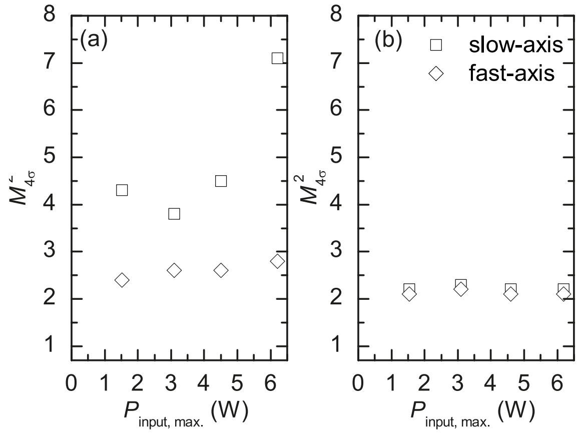
Coupling a DBR tapered diode laser beam into an SMF with a core diameter of approximately 6 µm has been investigated systematically. The experiments were conducted in a bench-top setup for four different operating points of the diode laser determined by the current injected in the taper section (I_{TP}). The optical power in front of the fiber could be adjusted in these tests without changing the laser radiation properties like beam quality and emission wavelength. As shown in Fig. 2, the power behind the SMF increased linearly with the power in front of the SMF for every operating point. The coupling efficiency was



< **Fig. 1.** Coupling efficiency into a single-mode fiber in dependence on fiber facet misalignment, measured at a constant operating point of the diode laser with input power reduced to 100 mW.



∧ **Fig. 2.** Power behind single-mode fiber (SMF) vs. power in front of SMF (T_{Laser} = 25°C, I_{RW} = 400 mA).



∧ **Fig. 3.** Beam quality parameter $M^2_{4\sigma}$ before (a) and after (b) coupling into the single-mode fiber.

lower for every successive operating point, which is in good agreement with simultaneously degrading diode laser beam quality in the slow axis (Fig. 3a). A maximum output power of 3.5 W was obtained at a coupling efficiency of 65%. This is, to best of our knowledge, the highest power value ex SMF achieved with a diode laser up to date. A stigmatic, nearly Gaussian laser beam was obtained behind the SMF. Results of the corresponding beam quality measurements are independent of the transversal direction (fast and slow axis) as well as of the operating point (Fig. 3b). Changes in the spectral properties of the DBR tapered diode laser were observed during fiber coupling experiments. This could be attributed to optical feedback, but the optical spectrum remained within 0.3 nm at all times. These results pave the way for high-power single-frequency laser sources emitting in the wavelength range 900 nm…1100 nm.

This ongoing work is funded by the German Federal Ministry of Education and Research in the frame of the InnoProfile-Transfer joint research project "FaBriDi" under contract No. 03IPT613A.

Anwendungen wie das Pumpen von Festkörper- und Faserlasern sowie die Frequenzkonversion erfordern effiziente Hochleistungslaser. Diese müssen im Dauerstrichbetrieb eine räumlich beugungsbegrenzte und spektral schmalbandige Strahlung im nahen infraroten Spektralbereich emittieren. Das Ferdinand-Braun-Institut arbeitet an der Formung der Strahlung von DBR-Trapezlasern, die anschließend in Single-Mode-Fasern gekoppelt wird. Dabei soll sowohl die hohe spektrale Strahldichte beibehalten als auch der Einsatz derartiger Halbleiterlaser deutlich vereinfacht werden. Zu diesem Zweck werden die Strahleigenschaften der DBR-Trapezlaser und der optischen Konfiguration für die Faserkopplung systematisch untersucht. Aktuell wird dabei eine maximale Leistung von 3,5 W aus einer Single-Mode-Faser mit einem Kerndurchmesser von ungefähr 6 µm bei einer Koppeleffizienz von 65% erreicht. Ziel sind kompakte Lasermodule, die hohe Ausgangsleistungen liefern und die dem Anwender einen stigmatischen und beinahe beugungsbegrenzten Strahl bieten.

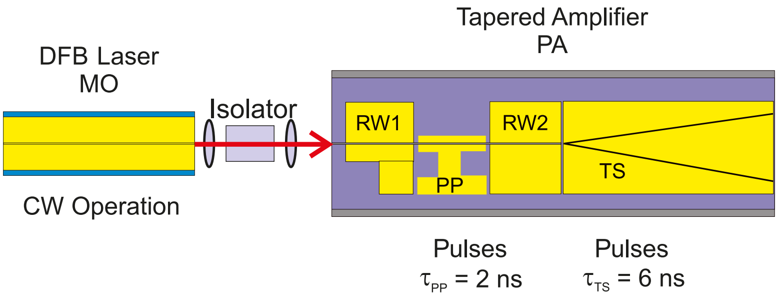
Publications

D. Jedrzejczyk, P. Asbahr, M. Pulka, B. Eppich, K. Paschke, "High-power single-mode fiber coupling of a laterally tapered single-frequency diode laser", IEEE Photonics Technol. Lett., vol. 26, no. 8, pp. 845-847 (2014).

D. Jedrzejczyk, P. Asbahr, M. Pulka, B. Eppich, K. Paschke, "Coupling of DBR tapered diode laser radiation into a single-mode-fiber at high powers," Proc. of SPIE vol. 8965, 89651A, (2014).

High-power wavelength-stabilized ns diode laser systems with narrow spectral linewidth for DIAL applications

Spectrally stable and nearly diffraction-limited optical pulses in the nanosecond range with an output power in the range of several ten watts are requested light sources for a variety of applications. This includes free-space optical communication, metrology, materials processing, frequency doubling, and light detection and ranging (LIDAR). The latter allows spatially resolved measurements of atmospheric constituents like aerosols and molecular gases. To measure gases using differential absorption LIDAR (DIAL) a narrow spectral linewidth is additionally needed. This spectral linewidth has to be smaller compared to the width of the air-broadened absorption lines under study at atmospheric pressure. In the case of water vapor (H_2O), for example, the emission linewidth should be smaller than 10 pm (0.1 cm^{-1}). The spatial resolution of such systems is determined by the pulse width of the light sources. A pulse width of 3 ns corresponds to a resolution down to 1 m. The repetition rate determines the possible measuring range, e.g., 1 MHz correlates to a range of 330 m.

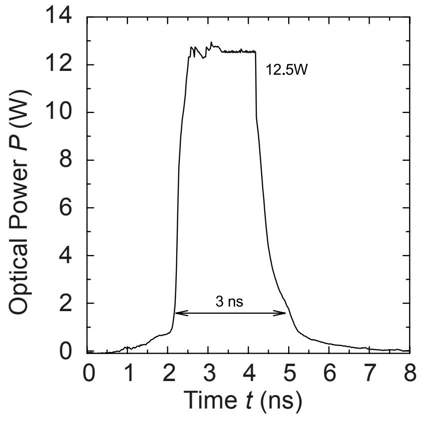


^ **Fig. 1.** Scheme of the FBH MOPA, using a DFB laser as master oscillator and a multi-section tapered amplifier as power amplifier.

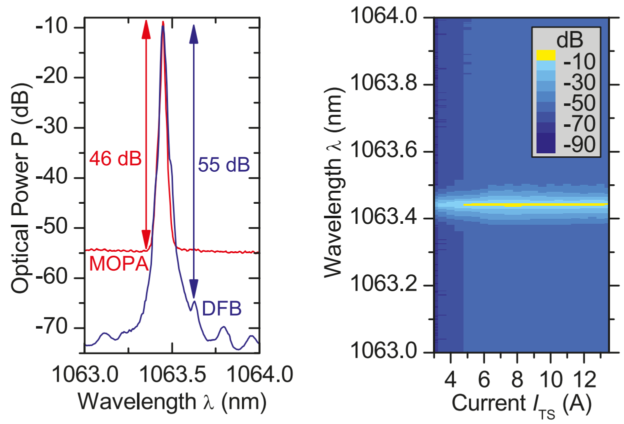
Very promising laser sources are Master Oscillator Power Amplifier (MOPA) systems, combining a wavelength-stabilized diode laser with a small spectral linewidth acting as master oscillator (MO) and a tapered amplifier used for power amplification (PA). In our case, a distributed feedback laser (DFB) is used as MO and a multi-section tapered amplifier as PA. A scheme of this MOPA is given in Fig. 1. The MO is operated in continuous wave (CW) operation and herewith guarantees the stable emission wavelength and the narrow linewidth. In our case, the DFB laser emits at 1063.5 nm with a spectral width below 10 pm and a side-mode suppression ratio of 55 dB. At first, the emitted light is collimated, then passes an optical isolator to prevent feedback, and is finally focused in the tapered amplifier. The optical power at the input facet of the PA is about 20 mW. The tapered amplifier consists of a 2 mm long ridge waveguide section, which is separated into three subsections (RW1, pulse picker PP, RW2), and a 4 mm long gain-guided tapered section (TS) with a full taper angle of 6°.

To control the input signal from the MO into the pulse picker (PP) section and to avoid large reabsorption in PP section, the RW1 section was driven with a CW current of about 10 mA. The current through the RW2 section was selected to limit the light coming from the TS towards the PP section. The pulse gating is performed with the PP section. Without current pulse, the PP absorbs the coupled CW beam. If a current pulse is injected, the PP becomes transparent and thus allows the optical beam to pass during the current pulse. The TS is also operated in pulsed mode to amplify the pulsed light after having passed the PP section.

A digital pulse and delay generator is used to provide the PP and TS pulses with an adjustable time delay between both pulse trains. The pulse currents are subsequently amplified with a GaN-based driver circuit, which has been also developed at the institute. This set-up provides nanosecond-range current pulses with a repetition rate up to 1 MHz (limited by the generator) and a peak current up to 20 A. In the studied parameter range, for the PP pulse a pulse length of 2 ns and a pulse length of 6 ns for the TS with a delay of 2 ns between PP and TS were found to provide the best results. For this evaluation, particularly pulse shape, peak power, and amount of amplified spontaneous emission were considered. A typical amplified optical pulse is shown in Fig. 2.



^ Fig. 2. Typical amplified optical pulse for the MOPA set-up.



^ Fig. 3. Spectral behavior of the MOPA – left: comparison of the side-mode suppression-ratio of the MO (DFB) and the MOPA; right: constant spectral emission over the full excitation range.

The peak power is 12.5 W, using a current of 13.5 A at the TS. The pulse width is about 3 ns and thus nearly identical with the electrical excitation. The amount of amplified spontaneous emission is smaller than 1%. The spectral behavior is shown in Fig. 3. The left side of Fig. 3 illustrates the side-mode suppression ratio (SMSR). For the MOPA, the SMSR is 46 dB and thus only slightly deteriorated compared to the DFB laser itself with 55 dB. The right side of Fig. 3 shows the spectral behavior of the MOPA when increasing the current through the TS, i.e., the peak power of the system. Here it can be seen that the emission wavelength at 1063.4 nm remains stable over the whole power range with a narrow spectral linewidth below 10 pm, limited by the spectral resolution of the spectrometer.

With the presented set-up, the basic principle of a high peak-power light source with a narrow spectral linewidth and stability is demonstrated. No saturation of the output power was observed, the output power was only limited by the available current supply. In the future, experiments with higher amplifier currents will be performed, and the emission wavelength of the MOPA system will be changed to that of the absorption lines of water vapor.

The work of the PhD student Thi Nghiem Vu involved in this project is supported by the Ministry of Education and Training of Socialist Republic of Vietnam (322_Project) and DAAD (code no. A/10/76664).

Für eine Vielzahl von Anwendungen werden spektral stabilisierte, nahezu beugungsbegrenzte Nanosekunden-Lichtquellen mit Ausgangsleistungen von einigen 10 Watt benötigt. Dazu gehört neben optischer Freiraum-Kommunikation, Metrologie, Materialbearbeitung auch die Messung von atmosphärischen Bestandteilen mittels LIDAR (light detection and ranging). Für diese Anwendung hat das FBH ein vollständig Diodenlaser-basiertes MOPA (master oscillator power amplifier)-System entwickelt, das es erlaubt, 3 ns lange Pulse mit einer Peakleistung von mehr als 12,5 W zu erzeugen. Die spektrale Breite der erzeugten Pulse liegt unterhalb 10 pm mit einer Seitenmoden-Unterdrückung von 46 dB. Auch bei Änderung der Ausgangsleistung bleibt die Emissionswellenlänge konstant. Lichtquellen, die auf diesem Prinzip basieren, werden künftig in Experimenten zum Nachweis von Wasserdampf eingesetzt.

Publication

N. Vu, A. Klehr, B. Sumpf, H. Wenzel, G. Erbert, G. Tränkle, "Wavelength stabilized ns-MOPA diode laser system with 16 W peak power and a spectral linewidth below 10 pm"; Semicond. Sci. and Technol., vol. 29, no. 035012 (2014).

For further information:

http://www.fbh-berlin.com/departments/optoelectronics

http://www.fbh-berlin.com/business-areas/diode-lasers

GaN Optoelectronics
GaN-Optoelektronik

Business Areas & Research
Geschäftsbereiche & Forschung

Im Geschäftsbereich GaN-Optoelektronik werden innovative Lichtquellen auf Basis des Halbleitermaterials Galliumnitrid (GaN) und seiner Legierungen AlGaN und InGaN entwickelt. Die Bandlücken dieser Materialien decken den gesamten sichtbaren und große Teile des ultravioletten (UV) Spektrums ab. Ziel ist es, die Leistungsfähigkeit dieser Lichtquellen stetig zu erhöhen, d. h. vor allem ihre Effizienz, Ausgangsleistung und Betriebslebensdauer. Zugleich werden Halbleiterlichtquellen mit völlig neuartigen Eigenschaften entwickelt, wie etwa Dioden mit einer Emission im tiefen UV oder mit integrierter Wellenlängenstabilisierung. Die Forschungs- und Entwicklungsarbeiten am FBH konzentrieren sich auf drei Klassen von Bauelementen: Laserdioden mit Emissionswellenlängen im blauen, violetten und gesamten UV-Bereich, Leuchtdioden (LEDs) für den gesamten UV-Bereich und solarblinde UV-Fotodetektoren. Die Anwendungsfelder dieser Bauelemente sind breit gefächert und reichen von der Atom- und Molekülspektroskopie, der Gassensorik bis hin zur Wasserdesinfektion, UV-Härtung und Fototherapie.

Das FBH arbeitet entlang der gesamten Wertschöpfungskette von Laserdioden und LEDs. Dabei werden zunächst die optischen und elektrischen Eigenschaften der GaN-basierten Bauelemente simuliert und anschließend die Heterostrukturen mittels Metallorganischer Gasphasen-Epitaxie (MOVPE) hergestellt. Nach der Prozessierung im Reinraum werden die Chips auf Wärmesenken oder in Gehäuse montiert und ihre elektrooptischen Eigenschaften vermessen. Das FBH arbeitet dabei im Rahmen seines „Joint Labs" in der GaN-Optoelektronik eng mit der Arbeitsgruppe „Experimentelle Nanophysik und Photonik" der TU Berlin zusammen. Zudem gibt es auf diesem Gebiet enge Kooperationen mit einer Reihe von nationalen und regionalen Industriepartnern. 2013 konnten zahlreiche neue Drittmittelprojekte eingeworben werden, unter anderem das Konsortium „Advanced UV for Life", das vom BMBF im Programm „Zwanzig20 – Partnerschaft für Innovation" gefördert wird.

Deutliche Fortschritte wurden im vergangenen Jahr bei der Reproduzierbarkeit im Bereich der Halbleiterepitaxie und der Chipprozesstechnologie erzielt. Breitstreifenlaserdioden, die im Wellenlängenbereich von 385 bis 440 nm emittieren, zeigen nunmehr reproduzierbare Schwellenstromdichten von 1,5 bis 4 kA/cm^2. Bei der Entwicklung von UV-Laserdioden konnte stimulierte Emission mit Rekordwellenlängen unterhalb von 240 nm unter optischer Anregung demonstriert werden. Gleichzeitig wurden Basistechnologien für die zukünftige Herstellung von Laserdioden mit verteilter Rückkopplung entwickelt. Dazu zählt insbesondere das Schreiben von Gittern hoher Ordnung, großem Tastverhältnis und präziser Tiefe in die Oberfläche von Laserschichtstrukturen.

Auch die Leistungsfähigkeit von UV-B-LEDs konnte gemeinsam mit der TU Berlin weiter gesteigert werden. Flip-Chip-montierte Bottom-Emitter-LEDs mit einer Emission bei 305 nm zeigen bei 20 mA Ausgangsleistungen von über 1 mW und Konversionseffizienzen > 1%. Je nach Betriebsstrom lassen diese Dioden in Langzeitstresstests Lebensdauern von über 10.000 Stunden erwarten, bevor die Leistung auf die Hälfte des Startwertes abfällt. Weiterhin wurde intensiv daran gearbeitet, mit UV-LEDs in den tiefen UV-C-Bereich vorzudringen. Insbesondere wurden niederohmige, hoch aluminiumhaltige AlGaN-Schichten auf epitaktisch lateral überwachsenen AlN-Schichten und AlGaN/AlGaN-Quantenfilme homogener Zusammensetzung entwickelt. Diese ermöglichen es, UV-LEDs mit einer Emission bei 235 nm zu realisieren. Mit diesen Fortschritten decken die UV-LEDs nun weite Teil des UV-A-, UV-B- und UV-C-Wellenlängenspektrums ab.

GaN Optoelectronics
GaN-Optoelektronik

The objective of the Business Area GaN Optoelectronics is to develop innovative light sources based on gallium nitride (GaN) semiconductors and its alloys AlGaN and InGaN. The band-gaps of these alloys cover the entire visible and even large parts of the ultraviolet (UV) electromagnetic spectrum. Goal is to steadily improve the performance of the light sources, particularly their efficiency, output power, and operation lifetime. The FBH is also developing novel semiconductor light sources, including light emitting diodes (LEDs) and laser diodes emitting in the deep UV as well as laser diodes with integrated wavelength stabilization. Research and development basically focus on three types of devices: laser diodes emitting in the blue, violet, and UV spectral range, LEDs covering the entire UV range, and solar-blind UV photodetectors. The fields of application for these devices are wide-ranging, from atom and molecule spectroscopy to sensing, water disinfection, UV curing, and phototherapy.

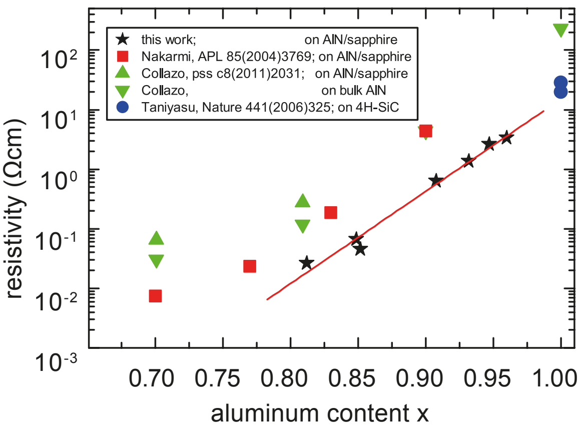
All research activities at the FBH are organized along the entire value chain from materials to device development, including the simulation of optoelectronic properties of GaN-based devices and growth of heterostructures by metal organic vapor phase epitaxy (MOVPE). After processing in the cleanroom, the chips are mounted onto heat sinks or into packages; finally, the devices are electro-optically characterized. Within its "Joint Lab" in the GaN optoelectronics field, the FBH intensively works together with the "Experimental Nanophysics and Photonics" group at TU Berlin. The Business Area GaN Optoelectronics also closely cooperates with numerous industrial partners, regional as well as Germany-wide. In 2013, once more a number of public research projects could be successfully raised, including "Advanced UV for Life". The consortium is funded within the framework of the "Zwanzig20 – Partnership for Innovation" program issued by the federal research ministry in Germany (BMBF).

In the last year, significant progress has been achieved in semiconductor epitaxy and chip processing technology. Broad area laser diodes on low defect density GaN substrates emitting in the wavelength range from 385 to 440 nm meanwhile reproducibly exhibit threshold current densities from 1.5 to 4 kA/cm^2. Within the scope of developing UV laser diodes stimulated emission under optical excitation was demonstrated with record short wavelengths below 240 nm. At the same time, the basic technologies for the future fabrication of Distributed Feedback (DFB) laser diodes have been developed, among them writing high-order gratings with large duty cycles and precise depth in the surface of laser layer structures.

In collaboration with the TU Berlin, the performance of UV-B LEDs has been further improved. Flip-chip mounted LEDs emitting around 305 nm show output powers of more than 1 mW and conversion efficiencies > 1 % at 20 mA. Based on long-time stress tests, the devices are expected to have life-times of more than 10,000 hours – depending on the operation current – before the power drops to half the initial value. Moreover, great effort was made to expand the emission wavelength of UV LEDs to the deep UV-C region. Particularly, the development of low-resistive Al-rich AlGaN layers on epitaxially laterally overgrown AlN layers as well as AlGaN/AlGaN quantum films of uniform composition allowed to realize UV LEDs with an emission near 235 nm. Based on these advancements, large parts of the UV-A, UV-B and UV-C wavelength spectrum are now covered by UV LEDs.

Epitaxial growth of AlGaN for deep UV-C LEDs and lasers

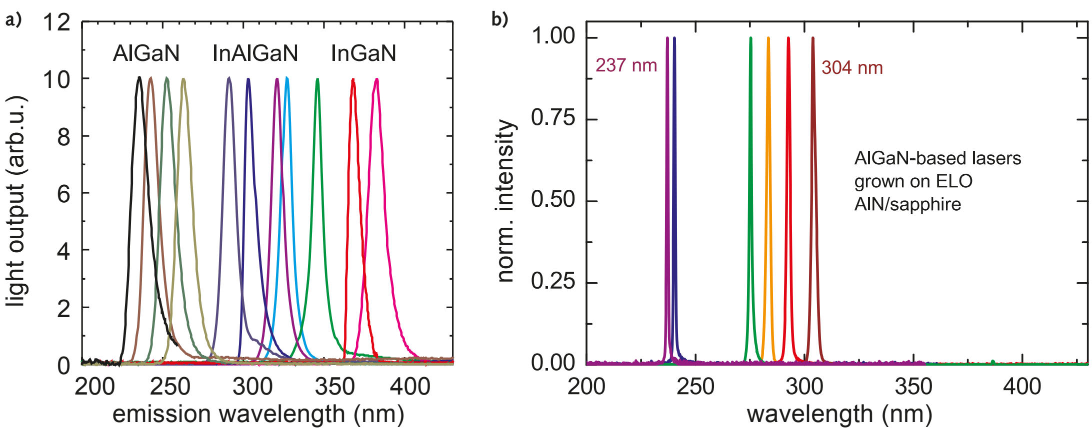
At present, mercury-based UV-C discharge lamps are used for water purification, photochemical curing, and many other applications. Prospectively, they could be partially replaced by light emitting diodes (LEDs) emitting in the ultraviolet (UV) C region, the wavelength range between 200 nm and 280 nm. That is because LEDs feature a compact size, are environmentally friendly, and adjustable in their wavelength. UV-C LEDs mostly consist of $Al_xGa_{1-x}N$ semiconductor layers with an aluminum mole fraction x > 0.5. The layers are grown by metal organic vapor phase epitaxy using the standard precursors TMAl, TMGa, and ammonia as well as hydrogen as carrier gas. Due to the low diffusion of Al adatoms on the AlGaN surface deposition temperatures well beyond 1000°C are needed to achieve a high material quality. Nevertheless, $Al_xGa_{1-x}N$ epitaxially grown on sapphire substrates usually has a high density of threading dislocations (TDD) in the range of 10^{10} cm^{-2}. The threading dislocations enhance non-radiative recombination of free charge carriers and reduce the emission efficiency of the LEDs as long as their density is ~10^9 cm^{-2} or higher. At the FBH, epitaxial lateral overgrowth (ELO) of AlN on patterned c-plane AlN/sapphire is used to reduce the TDD down to a few 10^8 cm^{-2} in the subsequent AlGaN heterostructures of the LED.



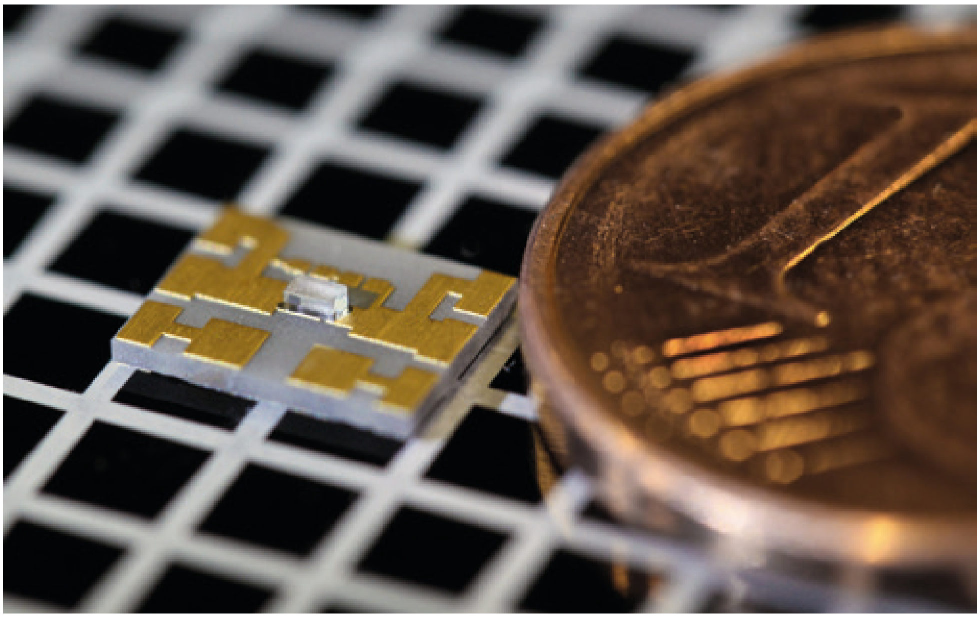
∧ **Fig. 1.** Resistivities of $Al_xGa_{1-x}N$:Si layers on ELO AlN/sapphire templates in comparison to literature data, Appl. Phys. Lett., vol. 103, 212109 (2013).

To realize low resistivity AlGaN layers with high aluminum mole fraction is one of the key challenges in developing UV-C LEDs and laser diodes. For $Al_xGa_{1-x}N$ with x > 0.7, as it is required for cladding layers in UV-C laser diodes or current spreading layers in UV-C LEDs, not only p-type, but even n-type conductivity is hard to achieve. This is due to both relatively high donor ionization energy and compensation of donors by extended defects and impurities. Therefore, $Al_xGa_{1-x}N$:Si layers with x > 0.7 are usually highly resistive despite high Si concentrations. Within the collaboration of the TU Berlin and the FBH to develop UV-C light emitters ELO AlN/sapphire templates with low TDD were used to realize conductive AlGaN:Si.

The layer resistivity was found to depend on the ratio of the group IV-III partial pressures with a pronounced minimum. A record low resistivity of 0.026 Ωcm for $Al_{0.81}Ga_{0.19}N$:Si was obtained under optimized conditions. The minimum resistivity increased almost exponentially with the aluminum mole fraction and reached 3.35 Ωcm for $Al_{0.96}Ga_{0.04}N$:Si, as shown in Fig. 1. Simultaneously the optimum IV-III ratio for a minimum resistivity decreased. Hall effect measurements showed that the increase of the resistivity is mainly caused by a



∧ **Fig. 2.** Emission spectra of a) UV-A, UV-B and UV-C LEDs and b) optically pumped UV-B and UV-C laser structures.



< **Fig. 3.** UV-LED flip-chip mounted on an AlN ceramic package.

decrease of the charge carrier density rather than the mobility. Optimized $Al_{0.81}Ga_{0.19}N$:Si layers exhibit a carrier concentration of 1.5 x 10^{19} cm^{-3} and an electron mobility of 16 $cm^2V^{-1}s^{-1}$ at room temperature. The obtained low resistivity allowed successfully realizing UV-C LEDs with AlGaN quantum wells as active region emitting at wavelengths down to 230 nm as shown in Fig. 2a. Considering the n-type conductivity for Al-contents x as high as 0.96, it should be possible to demonstrate even shorter emission wavelengths with LED structures on low TDD ELO templates.

Low dislocation densities are also important for the active regions in AlGaN-based laser diodes to obtain low lasing thresholds. By using the dislocation-density-reduced ELO AlN/sapphire templates, we were able to demonstrate optically pumped lasing for UV-C and UV-B laser structures between 237 nm and 304 nm, as shown in Fig. 2b.

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Leuchtdioden (LEDs), die im UV-C-Spektralbereich von 200 - 280 nm emittieren, könnten künftig Quecksilber-Dampflampen teilweise ersetzen. Zu den Anwendungen gehören beispielsweise die Wasserdesinfektion und das photochemische Aushärten von Beschichtungen. LEDs sind kompakt, ungiftig und ihre Wellenlänge lässt sich frei einstellen. Um ihre Effizienz weiter zu erhöhen, erforschen und entwickeln das FBH und die TU Berlin im Rahmen ihres Joint Labs n-dotierte AlGaN-Schichten mit niedrigem Widerstand. Voraussetzung dafür ist eine geringe Versetzungsdichte (TDD) unter 10^9 cm^{-2}. Andernfalls werden die Ladungsträger von Störstellen eingefangen und die Schichten isolierend. Mithilfe des epitaktischen lateralen Überwachsens (ELO) von AlN auf strukturiertem AlN/Saphir ist es gelungen, die TDD in den AlGaN-Heterostrukturen auf bis zu 10^8 cm^{-2} zu reduzieren und n-Leitung bis zu Al-Gehalten von 96 % zu erreichen. Dadurch können UV-C-LEDs mit AlGaN-Quantengräben als aktive Region bis hinunter zu Wellenlängen von 230 nm realisiert werden. Eine geringe Versetzungsdichte ist auch für AlGaN-basierte Laserdioden wichtig. Durch entsprechende ELO-Templates konnten optisch gepumpte Laserstrukturen zwischen 237 nm und 304 nm demonstriert werden.

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Highly reliable UV-B LEDs

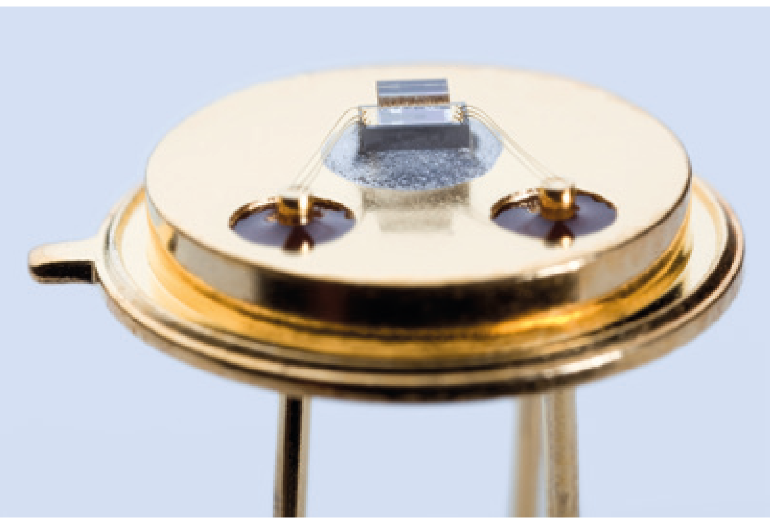
Over the last decade, considerable progress has been made in improving the optical output power of (AlGa)N-based LEDs emitting in the UV-B spectral region. UV-B LEDs are key enablers for industrial applications such as UV curing, plant growth lighting, and phototherapy. However, achieving long lifetimes and a good long-term stability of the electro-optical characteristics of UV-B LEDs remains a critical challenge. This also includes stable emission wavelength and operating voltages. Although UV-A LEDs already exhibit lifetimes exceeding 10,000 hours, the lifetimes of currently available UV-B LEDs is still limited to some 1,000 hours or less. Previous studies have shown that the crystalline perfection of the epitaxial layers as well as the materials and technologies used during chip processing influence the lifetime of these devices. However, the exact degradation mechanisms are not yet understood, this topic was therefore extensively explored at the FBH.

Our investigations included single-chip UV-B LEDs as wells as chips mounted on AlN-ceramic submounts as shown in Fig. 1 for better heat dissipation. All LEDs were featuring an emission wavelength around 305 nm and originated from a joint development effort between TU Berlin and the FBH. The devices were operated for up to 1,000 hours under varying stress conditions. Fig. 2 shows the evolution of the optical power over time of LED samples mounted on passively cooled copper heatsinks, which were stressed at 30 mA and 90 mA currents, respectively. Three different effects can be identified: (I) An increase of the optical power within the first hours of operation, (II) a strong decrease within the following hours, and (III) a slight gradual decrease for even longer times. Based on these observations two phases of different degradation can be defined. The so-called "burn-in" phase where the major changes correspond to the effects I and II. The next phase is exclusively dominated by the effect III and can be described as the "degradation" phase.

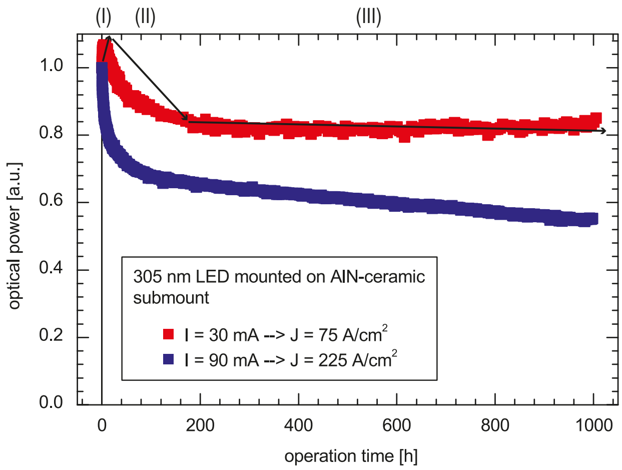
In order to obtain more information about the key factors that influence the burn-in phase of UV-B LEDs, lifetime tests with different drive-currents and temperatures in the active region have been carried out. Results of a single-chip UV-B LED burned in at 20 mA and a temperature alternating (in two hour intervals) between 122°C and 185°C in the active region are shown in Fig. 3a. It can be concluded that the effects I and II take place at the same time, while current and temperature in the active region determine which one of the two dominates. Effect I appears to originate from a stress induced by the drive current, whereas effect II seems to be triggered by drive current and temperature, as supported by the results shown in Fig. 3b.

Besides a change in the optical output power, other LED parameters vary during operation as well. One serious change concerns the current-voltage characteristic of the LEDs: Both the reverse-bias leakage current and the forward-bias leakage current below the band-gap are increasing with time. The increase is most evident within the burn-in phase and saturates after longer operation times, which correlates to the optical power degradation. It is known that the reverse-leakage current in GaN-based visible LEDs results from the tunneling of carriers across the active region, which is assisted by deep-level centers. Apart from that, the emission spectra do not change significantly over 1,000 hours of operation. This indicates that the structural integrity of the active region is quite stable during operation.

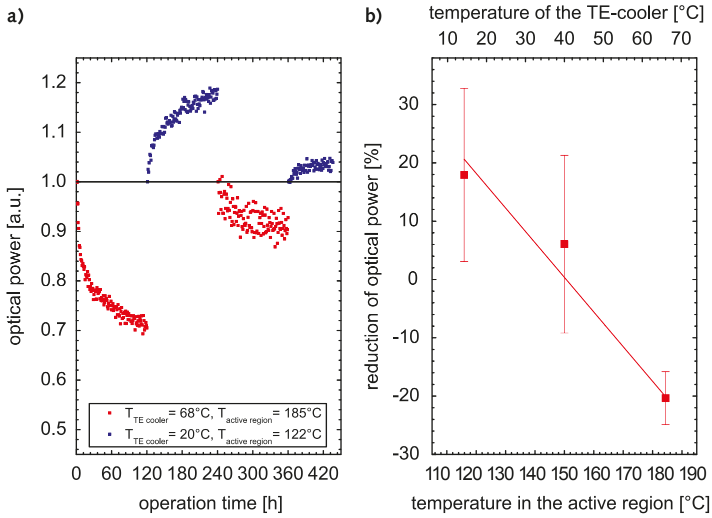
As mentioned before, the knowledge about the LED's lifetime is an important parameter. Due to the lack of experimental data of over 10,000 operation hours or more, a mathematical model is required to estimate the UV-B LEDs lifetimes. For LEDs the



^ **Fig. 1.** UV LED chip flip-chip mounted on AlN submount.



∧ **Fig. 2.** Degradation of optical power of 305 nm UV-B LEDs over time at operation currents of 30 mA and 90 mA. LEDs were passively cooled with copper heatsinks. The three degradation effects are marked by arrows and numbers.



∧ **Fig. 3. a)** Degradation of optical power over time of a (single-chip) 305 nm LED operated at 20 mA and alternating temperature in the active region.
b) Relative reduction of the optical power of a batch of LEDs after 60 minutes of operation as a function of temperature.

lifetime is typically defined as operation time until optical power has decreased to 70% (L70 level) or 50% (L50 level), starting after the burn-in phase. Using these definitions, a L50 lifetime of > 4,000 hours and > 10.000 hours for current densities of 225 A/cm² and 75 A/cm², respectively, can be estimated from the experimental data. These numbers are encouraging as they demonstrate the robustness and high reliability of our UV-B LEDs, particularly when considering that the degradation studies were carried out with LED chips which were not encapsulated under vacuum or inert gas.

The work was funded within the innovative regional growth core Berlin WideBaSe by the Federal Ministry of Education and Research under contract No. 03WKBT01C and No. 03WKBT01D.

Im Laufe der letzten Dekade konnten die Quanteneffizienzen von UV-B-LEDs schrittweise gesteigert werden. Dadurch werden diese Bauelemente auch für Anwendungen interessant, die bislang herkömmlichen UV-Strahlungsquellen vorbehalten waren. Allerdings sind die Lebensdauern von UV-B-LEDs zurzeit noch auf einige 1.000 Stunden begrenzt. Um längere Lebensdauern zu realisieren, müssen die physikalischen Mechanismen der Degradation besser verstanden werden, über die bislang nur wenig bekannt ist. Am FBH wurden daher Degradationsexperimente an UV-B-LEDs durchgeführt, die bei einer Wellenlänge von etwa 305 nm emittieren und die in enger Kooperation mit der TU Berlin entwickelt wurden. Je nach Zeitintervall konnten unterschiedliche Degradationsmechanismen identifiziert werden, die wiederum von den Stressfaktoren Betriebsstrom bzw. Stromdichte und Temperatur abhängen. So nimmt während der ersten Betriebsstunden die Emissionsleistung deutlich ab oder manchmal auch zu, was zum Einbrennen (Burn-In) der LED führt. Danach sinkt die Emissionsleistung langsam und graduell; dies definiert die eigentliche Lebensdauer der UV-B-LED. Durch Extrapolation von LED-Stresstests, die über 1.000 Stunden liefen, kann nun die L50-Lebensdauer (Abfall der optischen Leistung um 50%) auf über 10.000 Stunden bei einer Stromdichte von 75 A/cm² abgeschätzt werden.

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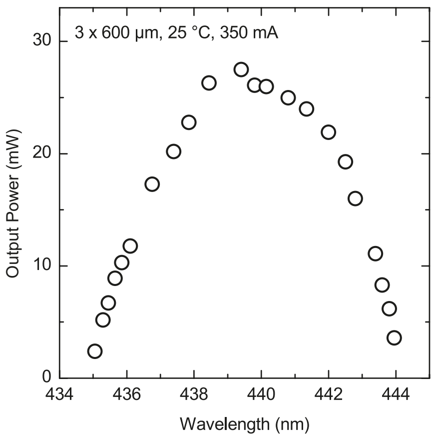
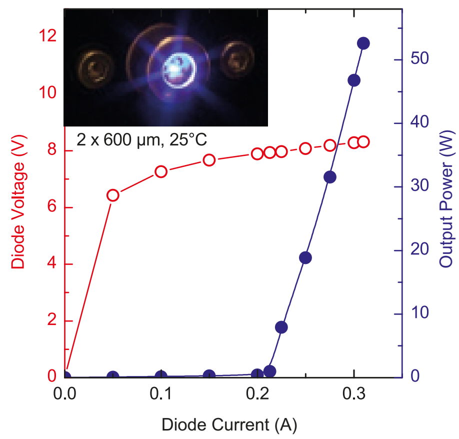
Low-threshold laser diodes for operation in external cavities

Tunable laser diodes emitting in the blue and violet spectral region are key components for various applications such as metrology, sensing, and atom spectroscopy. One way to realize such lasers is to combine a ridge waveguide (RW) laser diode (LD) with an external cavity, including a reflection grating as diffractive optical element. Therefore, low-threshold indium gallium nitride (InGaN) quantum well laser structures have been developed at FBH. Stable continuous wave (CW) lateral single-mode operation was demonstrated and RW laser diodes were provided with an anti-reflection coated front facet. These devices have been integrated by our partner eagleyard Photonics into an external cavity laser diode (ECDL) module in Littman-Metcalf configuration. Fig. 1 shows the tuning range of the ECDL around its peak wavelength of 439 nm with an emission power of 27 mW.

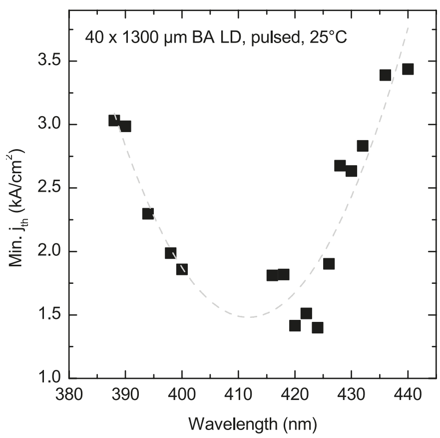
In order to obtain these results, an RW-LD process has been established at the FBH, allowing to reproducibly fabricate ridges as narrow as 1.5 µm. Fig. 2 shows an RW-LD packaged in a TO can and its characteristics in CW operation. In parallel, the epitaxial growth processes for InGaN multi-quantum well laser structures have been developed in order to improve the device performance and to allow modifying the heterostructure for specific



∧ **Fig. 1.** Light output power of an ECDL in Littman-Metcalf configuration measured at eagleyard Photonics.



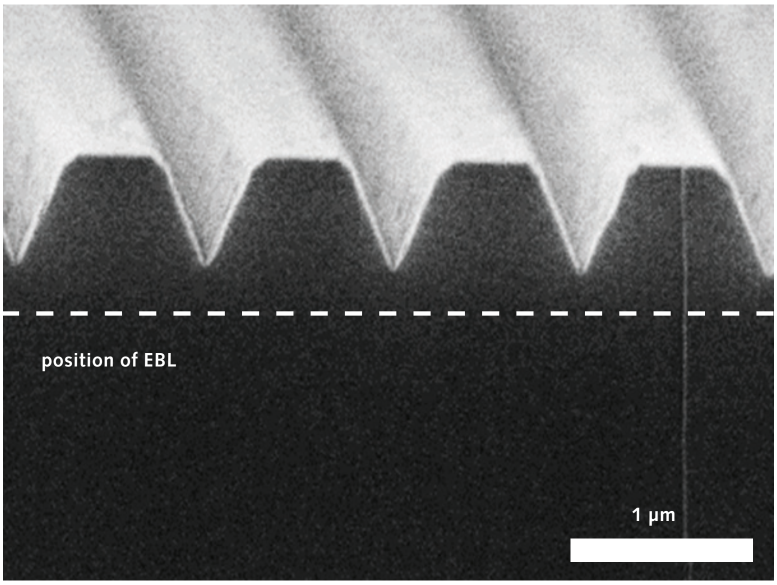
∧ **Fig. 2.** CW characteristics of a blue LD emitting at a wavelength of around 440 nm. Inset: LD packaged in a TO can.



∧ **Fig. 3.** Minimum threshold current densities of BA LDs fabricated at FBH. The segmented line is a guide to the eye.

applications. Epitaxy development focused on reducing the threshold current densities in the wavelength region between 385 and 440 nm. After a successful series of design optimizations and growth studies, we were able to significantly improve the reproducibility of the metal organic vapor phase epitaxy (MOVPE) process. In particular, the growth and cleaning cycle of the MOVPE system has been optimized, and certain reactor components were modified. Afterwards, various heterostructure designs and growth conditions were examined to realize threshold current densities as low as 1.5 kA/cm². Fig. 3 shows the minimum threshold current density achieved for various lasing wavelengths from the current generation of FBH laser structures. The data corresponds to uncoated broad area laser diodes (BA LDs) operated in pulsed mode. The minimum lasing threshold increases as the emission wavelength or the indium mole fraction in the active region increases, respectively. This effect can be attributed to both a reduced modal confinement at longer wavelengths and an inferior crystalline perfection of the active region at higher indium mole fractions.

The low threshold current densities of FBH's blue-violet laser diodes should allow to develop more complex devices, particularly LDs with monolithically integrated gratings. In order to realize distributed feedback (DFB) laser diodes, a technology to fabricate high order (≥ 10) V-shaped gratings with high aspect ratio on a GaN surface was developed.



∧ **Fig. 4.** Scanning electron microscopy image of a grating fabricated on a GaN surface.

Fig. 4 shows a scanning electron microscopy image of such a grating fabricated by using stepper lithography and plasma etching. The future work will focus on optimizing the grating geometry and the wave guiding heterostructure in order to realize longitudinal single mode DFB laser diodes for applications in sensing and spectroscopy.

The work was funded within the innovative regional growth core Berlin WideBaSe by the Federal Ministry of Education and Research under contract No. 03WKBT03B and No. 03WKBT03C.

Für eine Reihe von Anwendungen müssen blau-violette Laserdioden eine stabile und idealerweise durchstimmbare Wellenlänge bieten. Entsprechende Rippenwellenleiter-Laserdioden auf der Basis von GaN hat das FBH in Zusammenarbeit mit eagleyard Photonics in einem externen Resonator mit integriertem Reflexionsgitter realisiert; die Emissionswellenlänge kann um 9 nm durchgestimmt werden. Voraussetzung dafür war die Entwicklung einer Chiptechnologie, mit der sich 1,5 µm breite Rippenwellenleiter herstellen lassen und die den Dauerstrichbetrieb entsprechender monomodiger Laserdioden mit Ausgangsleistungen von über 50 mW ermöglicht. Gleichzeitig wurden das Heterostrukturdesign und das epitaktische Schichtwachstum soweit optimiert, dass nunmehr im Wellenlängenbereich 385 - 440 nm Breitstreifenlaser mit Schwellenstromdichten von nur 1,5 - 3,5 kA/cm^2 realisiert werden können. Basierend auf diesen Epitaxiestrukturen sollen in Zukunft komplexere Laserdesigns entwickelt werden, insbesondere Laserdioden mit verteilter Rückkopplung (DFB-Laserdioden). Auf Seiten der Chiptechnologie wurden erste erfolgreiche Schritte in diese Richtung unternommen, indem V-förmige Gitter hoher Ordnung mit hohem Aspektverhältnis in GaN-Oberflächen geschrieben wurden.

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For further information:

http://www.fbh-berlin.com/business-areas/gan-optoelectronics

Materials & Processes
Materialien & Prozesse

Business Areas & Research
Geschäftsbereiche & Forschung

Der Schwerpunkt der Aktivitäten in Technologieentwicklung und Materialforschung am FBH liegt auf der Vorlaufforschung zu Materialien und Prozessen. Sie liefert die technologischen Voraussetzungen für die gezielte Entwicklung von Bauelementen in den anderen Forschungsbereichen. Intensiv wird an Materialien auf der Basis von Galliumnitrid (GaN) gearbeitet, die in Leistungsbauelementen für Mikrowellen- und Leistungs-Schaltanwendungen, ultraviolett (UV) emittierenden Leuchtdioden (LEDs), Laserdioden und UV-Fotodetektoren zum Einsatz kommen. Ein Beispiel für die Materialforschung sind Wachstumsprozesse für GaN-basierte Hochvolt-Leistungstransistoren. Zur Herstellung der nitridischen Epitaxieschichten mittels Metal Organic Vapor Phase Epitaxy (MOVPE) stehen zwei Mehrscheiben-Epitaxieanlagen (AIX 2600 G3 HT) und eine kleinere Einzelwafer-Anlage für explorative Untersuchungen zur Verfügung. Damit können insbesondere Prozesse für bipolare Bauelemente mit p-Dotierung (LEDs, Laserdioden) von solchen für unipolare Bauelemente (GaN-HFETs, Fotodetektoren) getrennt bearbeitet werden. Dazu kommt eine weitere, kleinere Multiwafer-Anlage an der TU Berlin, die für die gemeinsamen Aktivitäten zu UV-LEDs genutzt wird. Auch an defektarmen AlN- und AlGaN-Schichten als Grundlage für UV-Bauelemente wird geforscht. GaN-Substrate sind von zentraler Bedeutung, insbesondere für GaN-basierte Laserdioden. GaN-Kristalle, aus denen solche Substrate herausgeschnitten werden können, werden am FBH mittels Hydride Vapor Phase Epitaxy (HVPE) gezüchtet. Die HVPE wird auch eingesetzt, um dicke AlGaN-Schichten als Templates für UV-LEDs abzuscheiden. Ein besonderer Fokus liegt auf der Kontrolle von Verspannungen bei GaAs-basierten Strukturen, da diese die Bauelementparameter und die Prozessierbarkeit der Wafer entscheidend beeinflussen.

Im Bereich der Prozesstechnologie wurden 2013 ein neuer Waferstepper (NIKON NSR-2205i12D) qualifiziert und die entsprechenden Lithografiemodule während des laufenden Prozessbetriebs umgestellt. Die neue Anlage erlaubt es, bis zu 350 nm kleine Strukturen fotolithografisch zu erzeugen. Neben der etablierten Technologie für GaAs-Laserdioden wurden robuste Prozessmodule für die Fertigung von GaN-basierten Hochleistungstransistoren weiter optimiert und entwickelt. Es wurden Verfahren für die Herstellung von Bauelementen für Anwendungen bei 33 - 50 GHz entwickelt. Zudem wurde eine Viatechnologie entwickelt, um elektrische Verbindungen von der Waferrückseite durch das SiC-Substrat hindurch zu Transistor-Kontakten auf der Wafervorderseite zu erzeugen. Ziele sind dabei vor allem eine hohe Reproduzierbarkeit, Ausbeute und Zuverlässigkeit. Bei GaN-basierten UV-LEDs und -Lasern wurde weiter intensiv an der Verbesserung von Ohm'schen Kontakten zu p-GaN und n-AlGaN gearbeitet. Überdies wurden Plasmaätzprozesse entwickelt, mit denen sich unterschiedliche periodische Strukturen in AlN und Saphir erzeugen lassen.

Gemeinsam mit Forschungs- und Industriepartnern bearbeitet das FBH zahlreiche Projekte: Unter anderem wurden im vergangenen Jahr (Al)GaN-basierte UV-Fotodetektoren für die Materialcharakterisierung weiter optimiert. Außerdem wurden besonders robuste Siliziumkarbid-Fotodetektoren hergestellt, die die Basis für anhaltendes wirtschaftliches Wachstum des Industriepartners sind. Für spektroskopische Anwendungen im Terahertz (THz)-Bereich wurden GaAs/AlGaAs-Quantenkaskadenlaser erfolgreich auf Heterostrukturen des Paul-Drude-Instituts prozessiert. Zusätzlich wurde die Technologie zur Herstellung von THz-Quantenkaskadenlasern mit verteilter Rückkopplung (distributed feedback, DFB) entwickelt und der Einfluss von Geometrieparametern auf die Emissionsspektren studiert.

Die Technologie zur Realisierung von InP-basierten Heterobipolartransistoren (HBTs) mittels Transfer-Substrat (TS)-Prozess wurde 2013 erfolgreich weiterentwickelt. In einem gemeinsamen Projekt mit dem Leibniz-Institut für innovative Mikroelektronik (IHP) zur dreidimensionalen Heterointegration von InP-HBTs in einen Silizium-CMOS-Prozess wird diese TS-Technologie vom FBH weiter „veredelt". Kombiniert man die beiden komplementären Technologien, entstehen vollkommen neuartige hybride Chips für höhere Leistungen im THz-Bereich. Die Entwicklungen zu Planarisierungs-, Verbindungs- und Via-Technologien führten zu einem präzise ausgerichteten Waferverbund mit höchstfrequenztauglichen Verbindungen zwischen den CMOS- und InP-HBT-„Welten".

Materials & Processes
Materialien & Prozesse

Activities in the development of materials and technology are focused on exploring materials and process modules, paving the way to fabricate advanced devices. The Materials Technology and Process Technology Departments provide the technological preconditions to develop devices that are realized in the respective research areas. Materials based on gallium nitride (GaN) are subject of intensive research and are utilized for power transistors for microwave and power switching applications as well as laser diodes, UV LEDs, and UV photodetectors. For example, epitaxial layers for GaN power transistors optimized for high operating voltages are based upon the development of corresponding processes in metal organic vapor phase epitaxy (MOVPE). The variety of different device structures is grown in two multi-wafer reactors (AIX 2600 G3 HT) and a smaller single-wafer machine for explorative work. This allows separating the developments regarding bipolar devices with p-doped layers (LEDs, laser diodes) from that of unipolar devices (GaN-HFETs and UV photodetectors). Another small multi-wafer system at TU Berlin is used in the joint work on UV LEDs. Also, AlN and AlGaN layers with reduced defect density for UV LEDs are being developed. GaN substrates are of pivotal importance, especially for GaN-based laser diodes. At FBH, GaN crystals for such substrates are grown using hydride vapor phase epitaxy (HVPE). HVPE is also applied to deposit thick AlGaN layers as templates for UV LEDs. A special focus is on controlling tensile strain in GaAs structures, as they significantly influence device parameters and processability.

In 2013, a new wafer stepper (NIKON NSR-2205i12D) was qualified and the corresponding lithography modules were adjusted without interrupting the process line. With this new photolithography tool feature sizes down to 350 nm can be fabricated. Beside maintaining and refining mature process modules for GaAs-based lasers, reliable and robust processes for GaN-based high-power transistors were further developed, e.g., for applications targeting 33 - 50 GHz. One particular focus was on the development of a stable technology for through substrate vias in 4" SiC to form short electrical interconnects between front contacts and the backside of the AlGaN/GaN transistors. Main objectives are high reproducibility, yield, and reliability. Regarding UV LEDs and GaN laser diodes, the FBH continued to further improve the reliable ohmic contacts to p-GaN as well as to n-AlGaN. Additionally, plasma etching recipes were developed to create periodic structures in AlN and sapphire. AlN and GaN layers, epitaxially grown on such substrates, exhibit low defect density and low strain.

Besides basic developments in epitaxy and process technology, external services such as delivery of epitaxial wafers, customer-related wafer processes, and analysis of device structures continued to be an integral part of FBH's work in the materials and processes field. Moreover, joint projects with research and industrial partners were successfully advanced. The development of (Al)GaN photodetectors, for instance, both as device and tool for the characterization of epitaxial layers has been further promoted. The ongoing successful R&D cooperation on robust silicon carbide photodetectors is the basis for sustainable economic growth of the industrial partner. GaAs/AlGaAs-based distributed feedback (DFB) quantum cascade lasers were successfully developed on heterostructures grown at Paul-Drude-Institute; emission spectra for different DFB laser geometries were jointly studied. Such lasers can be applied in THz spectroscopy.

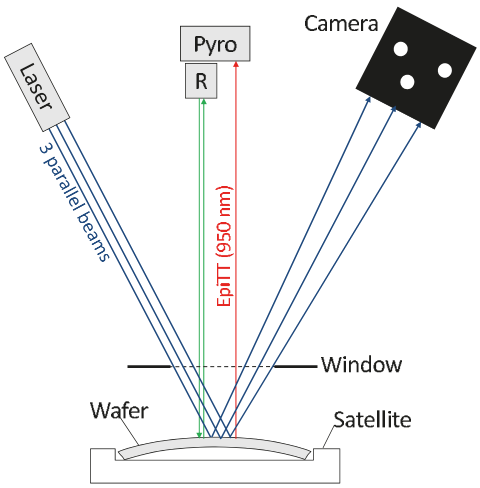
InP-based hetero bipolar transistors (HBTs) have been further developed in 2013, using the transferred-substrate (TS) approach. In collaboration with the Leibniz-Institut für innovative Mikroelektronik (IHP), the TS technology is further advanced for three-dimensional hetero-integration of InP-HBTs into silicon-germanium BiCMOS. This Leibniz project successfully combines the complementary technologies, thus creating entirely novel hybrid chips. They have the potential for higher powers in the THz range. Research on planarization, assembly, wafer bonding, and via technologies for RF interconnects yielded precisely aligned sandwich-like wafer bonds connecting the, up to now, separate CMOS and InP-HBT "worlds".

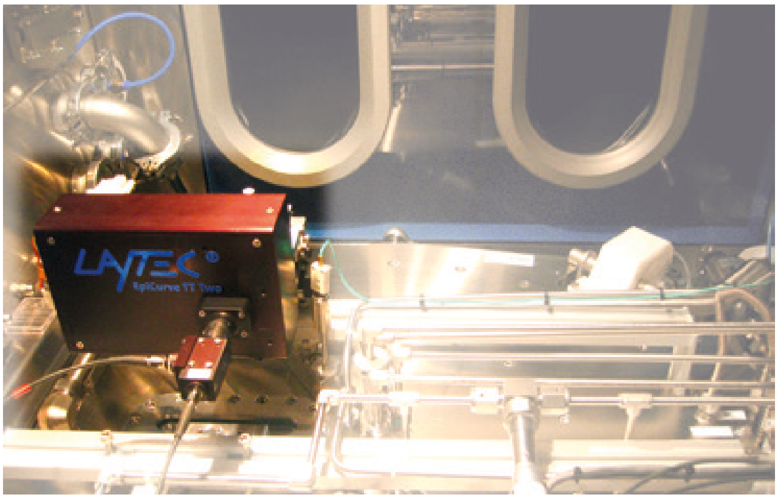
Strain compensation by $Al_xGa_{1-x}As_yP_{1-y}$

Laser diodes with very high output power are increasingly required for a number of applications like laser marking and cutting. One route to higher power is to spread the optical power over a larger area of the output facet in super large optical cavity (SLOC) device designs. This can even be expanded by stacking multiple lasing stages on top of each other in bipolar cascade lasers (BCL). Such designs often require thick layer stacks (10 µm or more) with a high Al content. Although the strain of an AlAs layer on GaAs at room temperature is typically low (ε_{AlAs}@RT ~ 0.14 %), when combined with such layer thicknesses it results in significant wafer bow. This may cause problems during the device process and also negatively affect device reliability.

By adding P to AlGaAs the lattice constant can be reduced to exactly match that of GaAs at RT. Unfortunately, the thermal expansion coefficients of AlAs and GaAs are different. While AlGaAs is nearly lattice matched to GaAs in the range of typical growth temperatures around 750°C (e.g. ε_{AlAs}@750°C < 0.02 %), $Al_xGa_{1-x}As_yP_{1-y}$ can be under tensile strain resulting in dislocation formation and strain relaxation already during growth. Thus, the composition and thickness of such strain compensation layers has to be optimized to avoid relaxation during growth and to minimize wafer bow during processing.

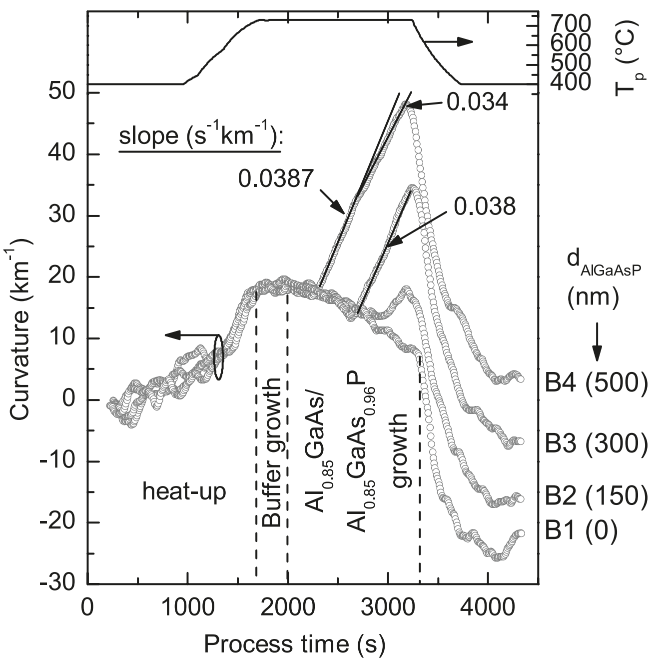
Therefore, the impact of $Al_{0.85}GaAs_{0.96}P$ layers on the strain evolution has been studied. For this purpose, in-situ monitoring of the wafer curvature during MOVPE growth has been performed using a LayTec EpiCurve TT© Two AR sensor (Fig. 1). The in-situ curvature measurement is based on laser deflectometry. Measurement of the wafer reflectivity at 633 nm and 950 nm yields information on growth rates and morphology while pyrometry at 950 nm allows assessment of the temperature of the wafer surface.



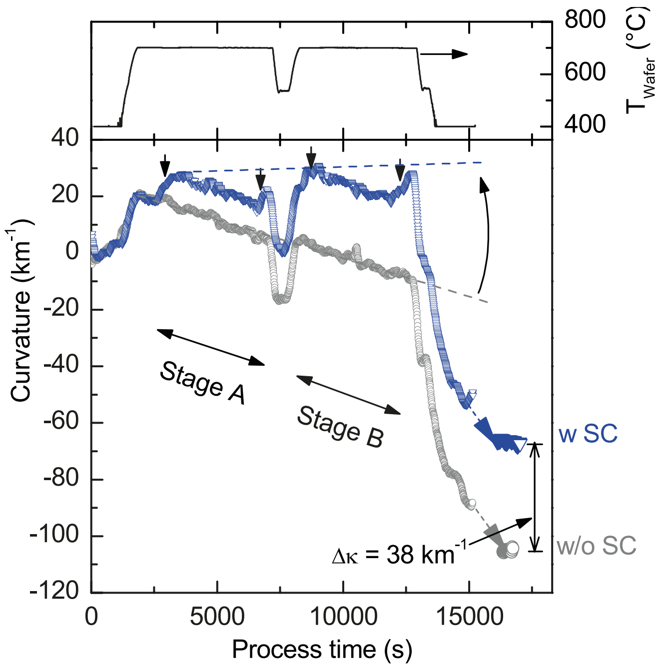


^ **Fig. 1.** Left: Schematic of the in-situ measurement setup including curvature (blue lines), reflectivity (green lines) and pyrometric wafer temperature measurement (red line). Right: In-situ curvature measurement head mounted on top of the reactor lid window.

The curvature transients in Fig. 2 show that if parts of a 650 nm thick $Al_{0.85}GaAs$ single layer are replaced by $Al_{0.85}GaAsP$ the curvature slope changes and the layer gets under increasing tensile stress. The initial shift towards concave wafer bow during heat up observed for all cases is simply the outcome of the heated wafer back side being hotter and thus more expanded than the cooled wafer front side. Distinct differences show up once the $Al_{0.85}GaAs_{0.96}P$ layer growth starts. The thicker the tensile strained $Al_{0.85}GaAs_{0.96}P$ layer, the more the RT convex wafer bow is being reduced, with sample B4, where 500 nm have been grown with adding P, being almost flat at RT. However, when comparing the curvature slopes of samples B3 and B4, the latter shows a characteristic kink. This correlates to X-ray diffraction curves that indicate that B4 is no longer pseudomorpically grown, but that the strain present during growth is already partly relaxed.



^ Fig. 2. In-situ curvature transients of sample series with gradually increasing $Al_{0.85}GaAs_{0.96}P$ layer thickness.



^ Fig. 3. In-situ curvature transients of 2-stage BCL with (blue) and without (grey) $Al_{0.85}GaAs_{0.96}P$ strain-compensating (SC) cladding layers.

Based on these findings we replaced the $Al_{0.85}GaAs$ cladding layers of a 2-stage BCL, with each cladding having a thickness in the range of 230 nm - 350 nm. Fig. 3 shows the curvature transients of a BCL with (blue triangles) and one without (grey circles) $Al_{0.85}GaAs_{0.96}P$ strain-compensating (SC) layers. Vertical arrows in Fig. 3 flag the positions of the four SC layers. They are designed so that the wafer curvature is kept nearly constant during growth, which results in a room temperature curvature decrease by 38 km^{-1}. This compensation scheme yields wafers with considerably less bow at RT and at the same time avoids relaxation during growth. This paves the way to dependable processing of reliable high-power laser diodes.

Part of the work is funded by the German Research Foundation (DFG) under contract No. WE1908/6-1.

Anwendungen wie etwa das Laserschneiden oder -beschriften erfordern Laserdioden mit hohen Ausgangsleistungen. Durch Vergrößern der Lichtaustrittsfläche auf der Laserfacette lässt sich deren verfügbare Ausgangsleistung erhöhen. Dies kann durch dicke AlGaAs-Schichtpakete erreicht werden. Allerdings biegen die Halbleiterscheiben bei Raumtemperatur dann stark durch. Die kompressive Spannung lässt sich durch Zugabe von P reduzieren, was jedoch bei den eingesetzten Wachstumstemperaturen um 750°C zu Zugverspannung führt. Relaxation dieser Zugverspannung über Versetzungen verringert wiederum die Zuverlässigkeit von Laserdioden dramatisch. Jedoch kann durch Messung der Krümmung der Halbleiterscheiben die Schichtzusammensetzung und Schichtdicke von $Al_xGa_{1-x}As_yP_{1-y}$-Schichten so eingestellt werden, dass die Verspannung beim Wachstum unterhalb der kritischen Grenze für Versetzungsbildung bleibt. Gleichzeitig ist die Durchbiegung im Waferprozess ausreichend gering. Ein zweistufiger bipolarer Kaskadenlaser, bei dem die vier $Al_{0,85}GaAs$ Mantelschichten durch $Al_{0,85}GaAs_{0,96}P$ ersetzt wurden, lässt sich so mit einer um 38 km^{-1} verringerten konvexen RT-Krümmung realisieren.

Publications

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A. Maaßdorf, U. Zeimer, M. Weyers, "MOVPE-grown $Al_xGa_{1-x}As_yP_{1-y}$ strain compensating layers on GaAs", J. Cryst. Growth, vol. 370, pp. 150-153 (2013).

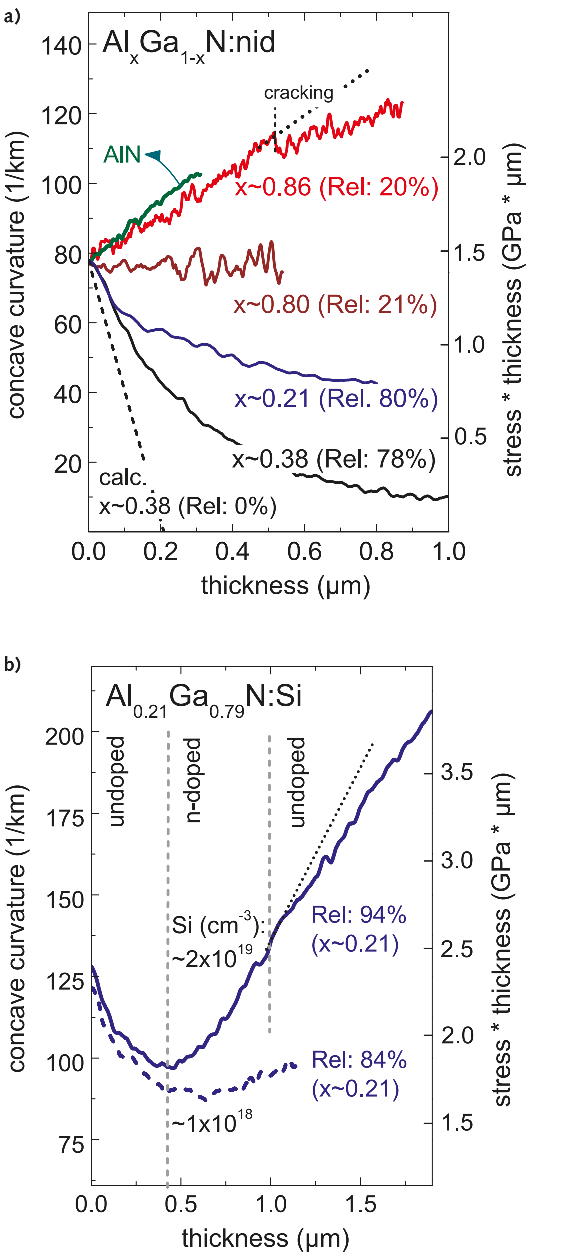
Stress evolution during $Al_xGa_{1-x}N$ growth

Transparent and conductive (Al,Ga)N epitaxial layers with low defect density are prerequisite for efficient UV LEDs. A well-known route to reduce the defect density during heteroepitaxy is the growth of thick layers in which dislocations can react with each other leading to mutual annihilation. However, the considerable lattice mismatch between AlN and GaN of 2.3 % induces lattice relaxation of such thick AlGaN layers, resulting in defect formation up to cracking of layers under tensile strain. Hence, AlGaN growth on AlN buffer layers resulting in compressive layer stress is mandatory.

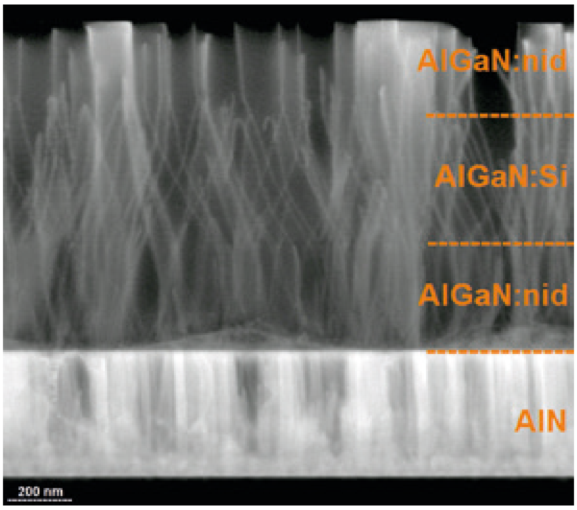
Within the 'Berlin WideBaSe' initiative, stress evolution during $Al_xGa_{1-x}N$ growth in a broad composition range (x ~ 0.2 to x ~ 0.9) has been investigated by in-situ wafer curvature measurements. Epitaxial growth was carried out in an AIX2600G3-HT MOVPE system equipped with a LayTec EpiCurveTT-AR© sensor, featuring wafer-selective measurements of reflectance, wafer-pocket temperature, and wafer curvature. Both planar and defect-reduced epitaxially laterally overgrown (ELO) AlN-sapphire templates have been employed.

Fig. 1a shows curvature changes during growth of different $Al_xGa_{1-x}N$ layers on planar AlN-sapphire. The denoted degree of relaxation has been measured ex-situ by high-resolution X-ray diffraction. AlGaN growth on AlN starts with a concave wafer bow due to the tensile growth of the AlN buffer on the sapphire substrate (Fig. 1a, green curve). With the onset of AlGaN growth the concave wafer curvature is reduced (negative curvature slope), as would be expected for compressively strained growth only for the lower Al-containing layers having a larger lattice mismatch to the underlying AlN. The non-linear curvature change points to ongoing relaxation of compressive stress. This behavior is different from the more abrupt changes in curvature when tensile strain is relaxed by crack formation. In contrast to the more strongly mismatched Ga-rich ternaries, the high Al-containing layers show a vanishing curvature change (x ~ 0.8) or even a positive transient slope (x ~ 0.86). In that case, the tensile growth of the underlying AlN buffer layer is continued and the slight compressive strain of AlGaN is not visible in the wafer curvature.

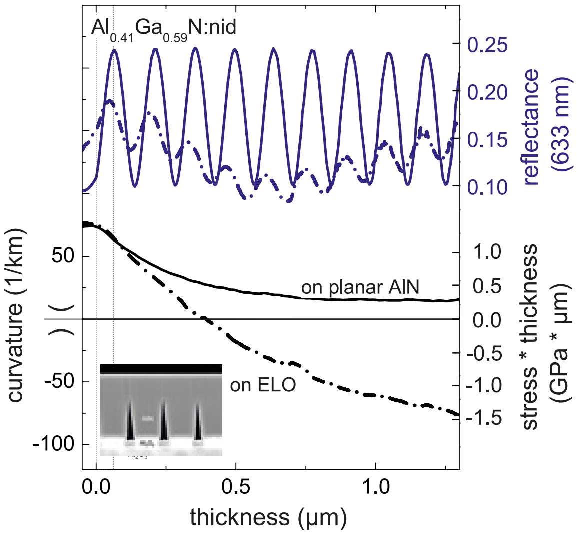
When adding Si to obtain n-doped layers the curvature trend drastically changes. Fig. 1b displays the curvature as a function of layer thickness for partially n-type doped $Al_{0.21}Ga_{0.79}N$ layers on planar AlN-sapphire. Introducing Si causes additional tensile strain, which reverts the curvature slope from negative to positive. This strain-mediating process takes place faster and to a higher extent with increasing doping level. Additional strain may lead to film cracking, which sets a limit for the achievable layer thickness and doping level. The reason for this strong impact of Si doping was studied by scanning transmission electron microscopy (STEM, see Fig. 2). First of all, the AlN/AlGaN:nid heterointerface region contains a large amount of strongly bent threading dislocation (TD) lines, resulting in dislocation interaction and their partial annihilation. Examining the AlGaN:nid/AlGaN:Si doping interface a pronounced dislocation inclination is visible. Similar to recent findings in GaN it is suggested that the observed inclination is not a true bulk climb process since this would be highly thermodynamically unfavorable in conjunction with the measured stress increase. Therefore, surface-mediated TD climb triggered by Si ad-atoms may explain the measurements, which is confirmed by the almost instant onset of TD inclination with the start of Si doping.



∧ **Fig. 1.** In-situ measured curvature change vs. film thickness of a) undoped $Al_xGa_{1-x}N$ layers and b) Si-doped $Al_{0.21}Ga_{0.79}N$ layers on AlN-sapphire templates.



∧ **Fig. 2.** Cross-sectional ADF-STEM image of an AlN/ $Al_{0.21}Ga_{0.79}N$:nid/$Al_{0.21}Ga_{0.79}N$:Si/$Al_{0.21}Ga_{0.79}N$:nid layer stack.



∧ **Fig. 3.** Wafer curvature (black) and reflectance (blue) measured during growth of undoped $Al_{0.41}Ga_{0.59}N$ on planar and ELO AlN-sapphire. Inset: cross-sectional SEM image of the 5 µm thick ELO AlN-sapphire structure.

In order to confirm the role of extended defects like threading dislocations in the relaxation behavior, we compared the strain progress during AlGaN growth on templates with differing defect densities. Fig. 3 shows the in-situ measured wafer curvature and reflectance (633 nm) during growth of $Al_{0.41}Ga_{0.59}N$ on an ELO AlN-sapphire template with a defect density that is about an order of magnitude lower than that of the planar AlN-sapphire template used for comparison. The curvature transients show significant differences depending on the template used. While a gradual but clear stress relief for AlGaN growth on the planar AlN is observed, a prolonged preservation of compressive stress on the defect-reduced ELO template is visible. These results prove that the strain relaxation process is closely linked to the defect structure in the material. Using defect-reduced ELO templates demonstrates a way to achieve highly conductive layers of sufficient thickness while simultaneously minimizing the risk of crack formation. Thus, we persist following this route in the development of UV-C LEDs.

Part of this work was funded by the Federal Ministry of Education and Research in the frame of the project 'Berlin WideBaSe' under contract No. 03WKBT06B.

UV-transparente, leitfähige AlGaN-Schichten mit einer geringen Defektdichte sind die Basis für effiziente UV-LEDs. Entscheidend sind dabei die Kontrolle von Verspannung und Relaxation in diesen Schichten. Dies wurde im Rahmen der Berlin WideBaSe-Initiative in einem breiten Zusammensetzungsbereich mittels in-situ Krümmungsmessungen untersucht. Um Rissbildung zu vermeiden, wurde AlGaN auf AlN-Saphir-Templates abgeschieden, was zu kompressiver Verspannung führt. Die anfänglich konkave Waferkrümmung nimmt während des Wachstums von AlGaN-Schichten mit geringerem Al-Gehalt nichtlinear ab. Verursacht wird dies durch die fortschreitende Relaxation der kompressiven Verspannung. Wird Si als n-Dotierelement hinzugefügt, führt dies zu zusätzlicher tensiler Verspannung. Dies wird in einem veränderten Anstieg der Krümmungstransiente sichtbar. STEM-Messungen zeigen, dass diese Verspannungsänderung mit einem Abknicken von Durchzugsversetzungen korreliert. Dementsprechend weisen AlGaN-Schichten auf versetzungsreduzierten ELO-Templates ein verändertes Relaxationsverhalten auf. Damit lassen sich höhere Dotierungen und Schichtdicken ohne Rissbildung realisieren.

Publications

F. Brunner, A. Mogilatenko, V. Küller, A. Knauer, M. Weyers, "Stress evolution during $Al_xGa_{1-x}N$/AlN growth on sapphire", J. Cryst. Growth, vol. 376, pp. 54-58 (2013).

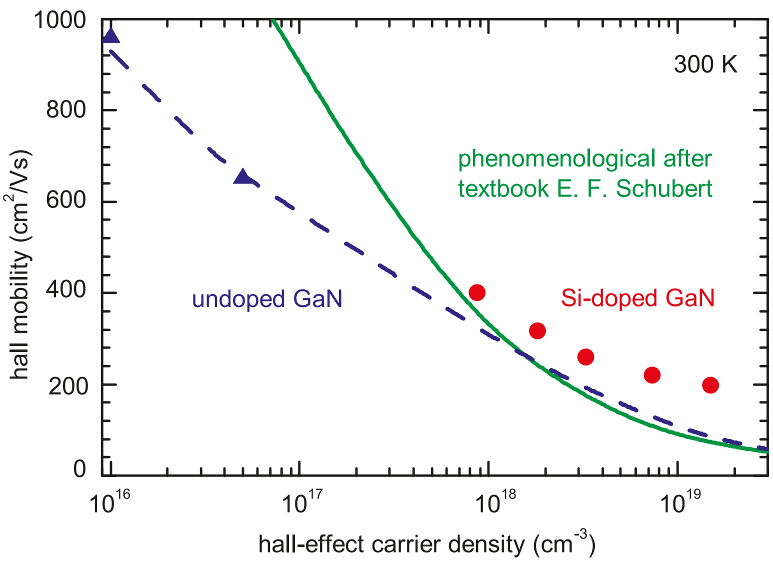
F. Brunner, A. Mogilatenko, A. Knauer, M. Weyers, J.-T. Zettler, "Analysis of doping induced wafer bow during GaN:Si growth on sapphire", J. Appl. Phys., vol. 112, no. 033503 (2012).

Si doping in GaN HVPE

Blue-violet laser diodes are used, for example, in "blu ray disc" storage devices. Currently, these laser diodes are grown on GaN substrates that are fabricated by heteroepitaxy in a "one wafer from one foreign substrate" approach. This procedure is costly and not compatible with mass production of white LEDs for lighting, which are therefore predominantly grown on foreign substrates. Since fabrication of such LEDs on GaN has been proven to yield advantages in device performance, there are ongoing activities worldwide to develop more cost-efficient processes. Additionally, these processes should yield conductive n-type substrates to reduce the resistance of the devices and increase their efficiency.

The FBH is contributing to these efforts by exploring the growth of thick GaN crystals by hydride vapor phase epitaxy (HVPE), which can then be sliced yielding several substrates from one boule. While Si is an established n-dopant for GaN, it has turned out that even for thin layers adding Si can result in tensile strain up to cracks. This observation is even more important for the growth of thick crystals, where avoiding such cracks is already a challenge without adding dopants. Thus, we have studied the compatibility of Si doping with our growth process for undoped boules at high growth rates of 400 µm/h and above in our vertical HVPE reactor.

In this process, GaN is grown by the reaction of ammonia (NH_3) with GaCl, which is formed in the reactor from liquid Ga and HCl. Important growth conditions are a temperature of 1010°C, a total pressure of 200 hPa, and a ratio of NH_3 to GaCl of 12 in a mixture of H_2 and N_2 as carrier gas, resulting in 400 µm/h growth rate. About 4 µm thick GaN layers on sapphire grown by MOVPE are used as starting templates. The first important finding is that dichlorosilane (SiH_2Cl_2) can be used under these conditions yielding efficient Si incorporation without causing problems like parasitic deposition. If Si doping is applied directly from the start of HVPE growth, tensile strain is generated resulting in cracked layers. Thus we have introduced an undoped, about 200 µm thick buffer layer that reduces the threading dislocation density (TDD) from 2 x 10^9 cm^{-2} in the template to less than 2.5 x 10^7 cm^{-2} at the start of Si doping. This avoids additional tensile strain showing that this strain is not due to Si doping itself, but caused by the interaction of Si and dislocations. By modifying the SiH_2Cl_2 flow the Si concentration was varied between 1 x and 16 x 10^{18} cm^{-3} with a high electrical activation of 90 % over this doping range. The lattice constants did not depend on the Si concentration, again showing that Si itself does not create strain. This is also confirmed by Raman spectroscopy performed in collaboration with Forschungszentrum Jülich. However, Si apparently affects the dislocation interaction since it slows down the reduction of the TDD after 1 mm of growth. While undoped layers show 2 x 10^6 cm^{-2} at the highest



< **Fig. 1.** Mobility vs. carrier density determined by Hall effect for Si-doped GaN and undoped GaN, which is n-type due to oxygen incorporation. Si doping results in higher mobilities since scattering by additional ionized point defects is reduced.

∧ Fig. 2. 2 inch 7 mm thick GaN crystal doped with 1 x 10^{17} cm^{-3} silicon. Eight GaN slices were cut by an industrial partner from this crystal.

∧ Fig. 3. Perspective view of the HVPE machine with glove boxes above and below the cabinet containing the vertical reactor.

doping level 2 x 10^7 cm^{-2} are still present for 1 mm thick layers. The results of the basic studies regarding doping with Si have been applied for growing a 7 mm thick GaN crystal on 2 inch at a Si doping level of 1 x 10^{18} cm^{-3}. The crystal has then been sliced into eight wafers by an industrial partner. This study proves the feasibility of Si doping or GaN boules grown by HVPE. Nevertheless, issues like avoiding cracks and V-pit formation indicate that further research is needed to improve the understanding of the mechanisms behind this process.

This work was funded by the Federal Ministry of Education and Research within the projects 01BU0621 and 16BM1202.

Das FBH züchtet dicke GaN-Kristalle mittels Hydridgasphasen-Epitaxie, mit denen sich mehrere GaN-Substrate kostengünstig parallel herstellen lassen. Diese sind nicht nur für die Produktion von Laserdioden, sondern auch von Weißlicht-LEDs attraktiv. Ein 7 mm dicker, Si-dotierter GaN-Kristall wurde bereits erfolgreich durch einen Industriepartner in acht Scheiben aufgeschnitten. Zunächst werden die Kristalle in einem vertikalen Reaktor mit hohen Raten von 400 µm/h bei 1010°C und einem Druck von 200 hPa aus Ammoniak und GaCl gewachsen. Um einen geringen Widerstand zu erzielen, wird Dichlorsilan als Quelle für Si, den etablierten Dotierstoff für Schichtstrukturen von Bauelementen, eingesetzt. Die bekannte Gefahr der Rissbildung durch Si wird dadurch gebannt, dass Dichlorsilan erst zugeschaltet wird, nachdem eine geringe Versetzungsdichte erreicht ist. Diese ist nach dem Wachstum einer 200 µm dicken undotierten Schicht von 2 x 10^9 cm^{-2} auf unter 2,5 x 10^7 cm^{-2} abgesunken. Si wird dann kontrolliert im Bereich von 1 x bis 16 x 10^{18} cm^{-3} eingebaut, wobei über 90% der Si-Atome auch freie Ladungsträger erzeugen. Dies ermöglicht GaN-Substrate mit minimiertem Widerstand und damit Bauelemente mit hoher Effizienz.

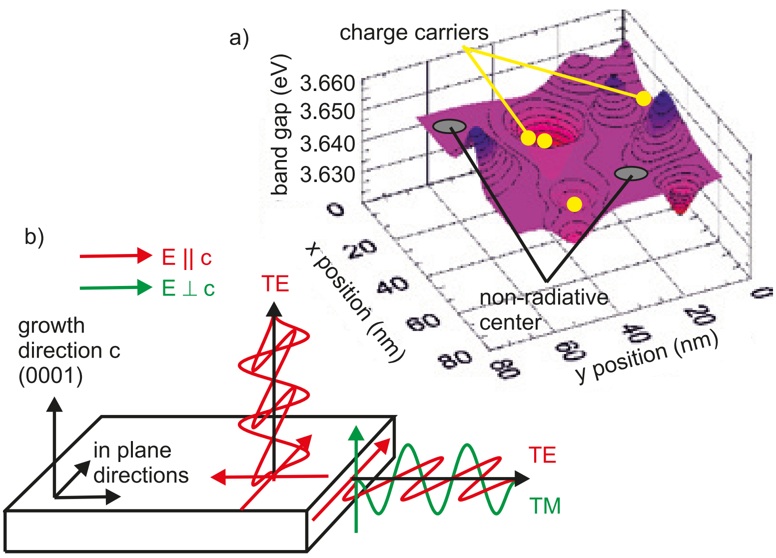
Publication

E. Richter, T. Stoica, U. Zeimer, C. Netzel, M. Weyers, G. Tränkle, "Si Doping of GaN in Hydride Vapor-Phase Epitaxy", J. Electron. Mater., vol. 42, no. 5, pp. 820-825 (2013).

Quantum efficiency of AlGaN and AlInGaN

Ultraviolet (UV) light emitting diodes (LEDs) with emission wavelengths from the UV-A to the UV-C spectral range are widely applicable in water purification, disinfection, sterilization, photo-chemical curing, and lithography. These LEDs are a safe, compact, and long-living alternative to currently used UV lamps. UV LEDs can be realized using the AlGaN material system which offers direct band gap emission between 200 nm (AlN) and 350 nm (GaN).

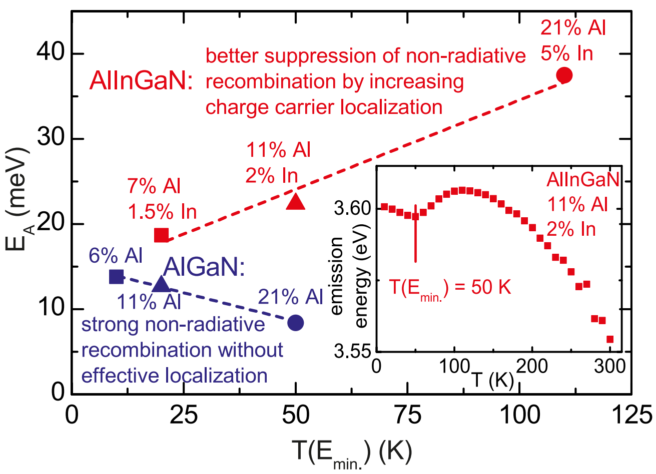
Several technological and physical challenges have to be faced in the process of developing AlGaN-based LEDs. First of all, there exists no adequate substrate for AlGaN epitaxial growth. Heteroepitaxial growth on sapphire substrates or growth on bulk GaN or AlN is used alternatively, resulting in large lattice and thermal expansion mismatch. This mismatch generates high densities of threading dislocations in the AlGaN layers, which act as non-radiative recombination centers and can even complicate device processing. Secondly, when the aluminum content increases the band structure changes in such way that the emission becomes transverse magnetic (TM) polarized. For growth of AlGaN in the generally used polar c direction, TM-polarized emission leads to a reduced light extraction out of the top surface of the heterostructure or through the substrate. It also increases the reabsorption probability when light emitted in parallel to the surface propagates along the active layer plane. Thirdly, doped AlGaN features low conductivity when the aluminum content is increased. The activation energies of silicon and magnesium dopants increase by several hundred meV with the band gap energy between GaN and AlN. For LEDs the low conductivity leads to reduced external quantum efficiency, heating of the device, and a higher probability of a burn-through of the p-n-junction.



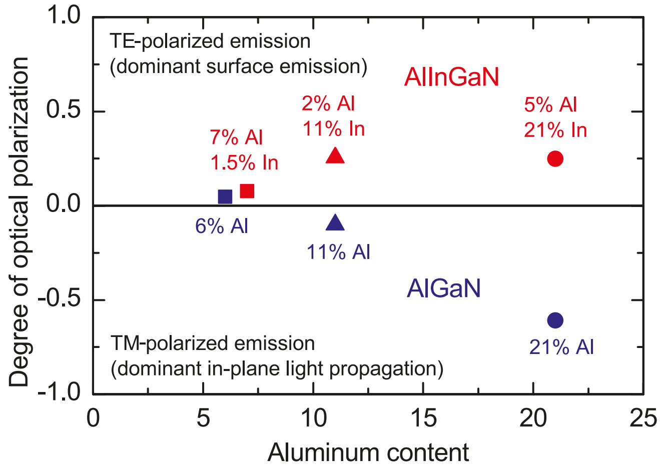
∧ **Fig. 1.** Sketches for Al(In)GaN: a) spatial band gap fluctuations resulting in charge carrier localization, b) orientations of electric field vectors E for TE- and TM-polarized light.

One possibility to eliminate at least some of these difficulties is to incorporate a small amount of indium in AlInGaN layers for UV-A emitting LEDs. The presence of indium is expected to enhance the charge carrier localization effect, which suppresses the transport of charge carriers to non-radiative recombination centers and thus increases the radiative recombination efficiency. It also can reduce stress and piezoelectric fields in quantum wells. Both effects should lead to higher internal quantum efficiency in AlInGaN active layers. Furthermore, by incorporating indium the polarization of the optical band gap transition becomes more transverse electric (TE). This increases the light extraction and the external quantum efficiency.

We have compared the internal quantum efficiency and the light polarization characteristics of UV-A emitting AlGaN and AlInGaN layers (320 - 350 nm) with similar emission wavelengths. By means of temperature-dependent photoluminescence we deepened the knowledge about the internal and external quantum efficiency characteristics in these materials. The incorporation of more than two percent of indium significantly increases the charge carrier localization and boosts the internal quantum efficiency by half an order of magnitude. Charge carriers in AlInGaN layers require a two- to threefold higher thermal energy to reach non-radiative centers by diffusion than charge carriers in AlGaN layers. Additionally, the light extraction efficiency at room temperature increases by about 20% due to the incorporation of indium. The reason for this effect is that the emission changes from dominantly TM-polarized for AlGaN to



∧ **Fig. 2.** Thermal activation energies for non-radiative recombination E_A plotted against temperature at local minimum in S-shaped E(T) behavior (compare inset) as measure for charge carrier localization.



∧ **Fig. 3.** Incorporation of indium in AlGaN causes a change from TM-polarized to TE-polarized emission.

dominantly TE-polarized for AlInGaN. The drawback when using AlInGaN layers is a broader spectral emission width and the limitation to the UV-A spectral range.

For UV-A LEDs these positive effects of AlInGaN are utilized in quantum wells (QWs). Effects on the valence band ordering in quantum wells shift the degree of polarization further to TE and enable even higher light extraction efficiency. Firstly, the quantization energy for light hole bands responsible for TM polarization is higher than for heavy hole bands. This makes TE-polarized transitions involving heavy hole bands in QWs more likely than in the bulk. Secondly, quantum wells are generally grown on higher band gap buffer material with smaller lattice constants. Accordingly, QWs are compressively strained. The compressive strain also affects the valence band ordering, increases the transition energy for heavy hole bands less strongly than for light hole bands, and further enhances TE-polarized emission. UV-A LEDs developed in close cooperation between TU Berlin and FBH make use of these advantages of AlInGaN QWs with strong TE polarization, leading to improved device performance.

This work was supported by the German Research Foundation (DFG) in the Collaborative Research Centre 787.

Zur Verbesserung der Effizienz von Leuchtdioden, die im UV-A-Spektralbereich emittieren, wurden AlGaN- und AlInGaN-Schichten und Quantengräben untersucht. Mittels temperaturabhängiger Photolumineszenz wurden die Quantenausbeute und Polarisation der Emission bestimmt. Werden mehr als zwei Prozent Indium in AlInGaN eingebaut, führt dies gegenüber AlGaN bei gleicher Wellenlänge durch stärkere Fluktuation der Bandlücke zu einer verstärkten Ladungsträgerlokalisation in den Schichten. Das hebt die thermische Aktivierungsenergie für nichtstrahlende Rekombinationsprozesse und erhöht die interne Quantenausbeute bei Raumtemperatur um etwa eine halbe Größenordnung. Zusätzlich führt die Beimischung von Indium zu einer Änderung der Valenzbandabfolge, was die Emission von transversal elektrisch (TE) polarisiertem Licht begünstigt. Das TE-polarisierte Licht kann über die Oberfläche oder durch das Substrat um etwa 20% besser ausgekoppelt werden. Damit lässt sich die externe Quantenausbeute weiter erhöhen.

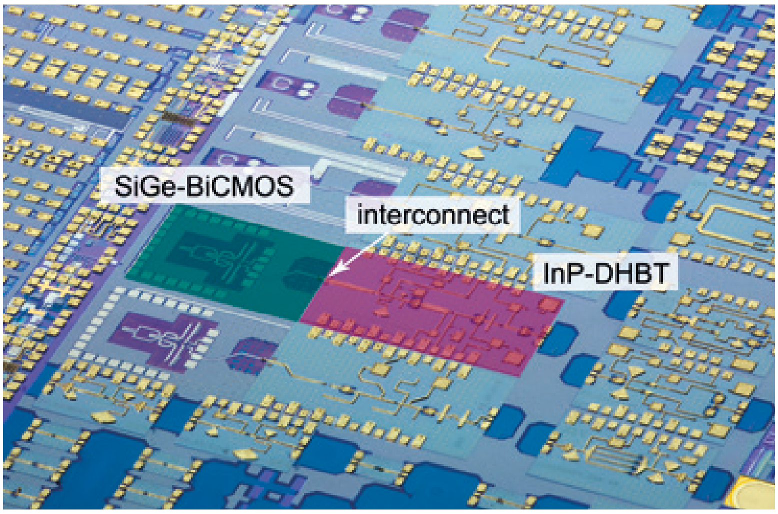
Publication

C. Netzel, A. Knauer, M. Weyers, "Quantum Efficiency Analysis of Near-Ultraviolet Emitting AlGaN and AlInGaN Structures", Jpn. J. Appl. Phys., vol. 52, no. 08JL14 (2013).

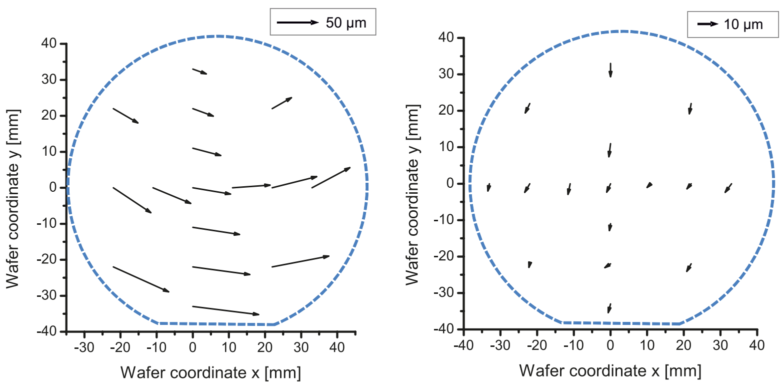
Three-dimensional InP-DHBT on SiGe-BiCMOS integration for millimeter-wave circuits by benzocyclobutene-based wafer bonding

High-frequency circuits based on indium phosphide (InP) which use hetero-bipolar transistors (HBT) are known to exceed the performance of silicon devices in terms of RF power and frequency range. This can be attributed to their high electron mobility and breakdown voltage. On the other hand, silicon is the dominating material of modern semiconductor technology offering established process modules, high functionality, unmatched integration density, complex circuit yield, and low production costs.

In order to realize a new class of components that benefit from both technologies, FBH has developed a heterogeneous integration process. This approach bases on a bonding process of InP-HBT wafers to silicon BiCMOS substrates. In a joint project, the Leibniz-Institut für innovative Mikroelektronik (IHP) delivers the silicon-based wafers, while FBH fabricates the III-V HBTs and implements the wafer level bonding process. The silicon and InP wafers are partly processed in parallel in the respective fabs of FBH in Berlin and IHP in Frankfurt/Oder.



∧ **Fig. 1.** Chip photograph of integrated circuits fabricated by BCB-based wafer level bonding.

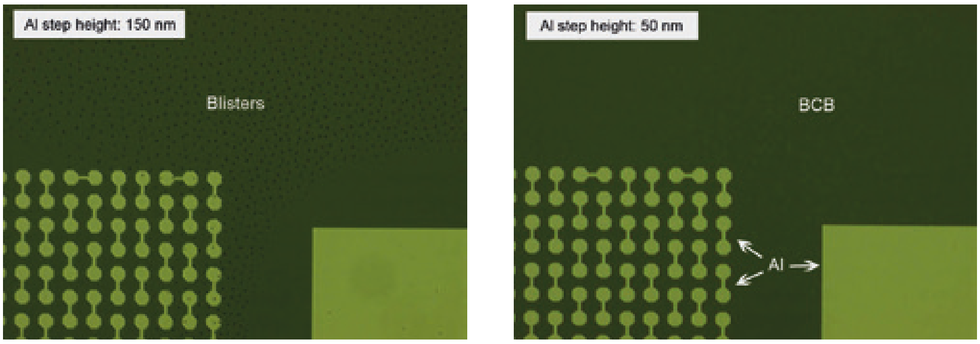


∧ **Fig. 2.** Displacement vector field for initial bond experiments (left) and after optimizing the bonding procedure (mean wafer shift is 57.5 µm and 6.4 µm, respectively).

Key process element is the wafer bonding process with BCB (benzocyclobutene). BCB is spin-coated on both wafers and afterwards soft-cured under nitrogen atmosphere. The wafers are aligned to each other by using proper registration marks and then mechanically clamped. In a bond tool, the wafer pair is pressed together and heated to 240°C. At this temperature, BCB will cross-link, leading to a permanent bond of the silicon to III-V wafer.

However, the bond process can induce significant translation of the two wafers relative to each other, resulting in displacements of 50 - 70 µm as depicted in Fig. 2 (left). Since the size of the landing pads is 15 µm, such misalignment is not tolerable. By carefully optimizing the mechanical clamping mechanism during alignment and bonding, final alignment accuracies of the wafer bonds in the range of 4 - 8 µm were obtained (see Fig. 2, right).

The total thickness of the bonding BCB should be as thin as possible, since it directly influences the vertical distance of the interconnects between InP and SiGe-BiCMOS. In order to ensure transitions with low insertion loss up to several hundred GHz, the stack thickness should be minimized. Furthermore, using thin BCB layers helps to achieve good alignment accuracies after the wafer bond process, as less slipping of the wafers during the bond process can be expected. On the other hand, this process is very sensitive to surface topography (see Fig. 3). Since both InP and SiGe-BiCMOS wafers are semi-processed, a certain topography is always present. Depending on the surface step heights, blisters might occur that



^ **Fig. 3.** Optical micrograph of glass wafers bonded to silicon wafers with aluminium steps of different heights. The step height of the structures significantly influences the bond result: A step height of 150 nm results in blisters, reducing it to 50 nm leads to defect-free bonding.

deteriorate the bond strength significantly. Strategies to overcome the issues induced by the surface topography and to optimize the bond process with sufficient adhesion have been developed at FBH.

This work aims to realize circuits in the sub-mm to sub-THz spectrum (100…500 GHz). The integration scheme is intended to join silicon and InP subcircuits on wafer level with broadband low-loss RF transitions connecting the subcircuits. This setup circumvents the otherwise needed mounting and packaging of the subcircuits, thereby significantly saving size, weight, and cost at system level. For example, using this technology a 164 GHz signal source has been demonstrated that consists of a BiCMOS voltage-controlled oscillator driving a chain of InP-HBT frequency doubler and InP-HBT power amplifier, delivering 1 mW of RF power (see also p. 68, InP-HBT-based circuits for the 200 GHz frequency band).

Funded by the Leibniz Association within the project SciFab, FBH and IHP are continuing the development of this unique technology.

Zusammen mit dem Leibniz-Institut für innovative Mikroelektronik (IHP) arbeitet das FBH an einer Technologie zur Heterointegration von elektronischen InP-DHBT-Bauelementen mit SiGe-BiCMOS-Technologie. Damit lassen sich die Vorteile beider Technologien kombinieren. Dies wiederum liefert den Schlüssel zur Realisierung von Anwendungen, die auf hohe Leistungen im Terahertz-Bereich abzielen. Kernstück der Integration ist ein Waferbond-Prozess mittels Benzocyclobuten. Der am FBH entwickelte Prozess erlaubt eine im Hochfrequenzbereich verlustarme Integration beider Wafer. Dabei stand eine hohe Justagegenauigkeit der Wafer zueinander ebenso im Fokus wie ein defektarmes Bondergebnis. Die Prozesstauglichkeit dieses Integrationsansatzes wird durch die realisierten kombinierten Schaltungen bestätigt.

Publications

I. Ostermay, F.-J. Schmückle, R. Doerner, A. Thies, W. Heinrich, O. Krüger, V. Krozer, T. Jensen, T. Krämer, M. Lisker, A. Trusch, E. Matthus, Y. Borokhovych, B. Tillack, “200 GHz Interconnects for InP-on-BiCMOS Integration”, IEEE MTT-S Int. Microw. Symp. Dig., Seattle, USA, Jun 2-7, WE2G-1 (2013).

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Processing of via interconnects for AlGaN/GaN HEMTs

Highly efficient high-power transistors based on AlGaN/GaN hetero-junction field effect transistors (HFETs) offer novel solutions for high-class applications, e.g. in radar and communication systems. To push operation frequency and power density to its limits is challenging for design and frontend processing, but also for backend of line processing and assembly. Silicon carbide (SiC) used as substrate material of choice for the AlGaN/GaN epitaxial layers is mechanically and chemically very resistive and requires sophisticated processing concepts to enable advanced interconnect design.

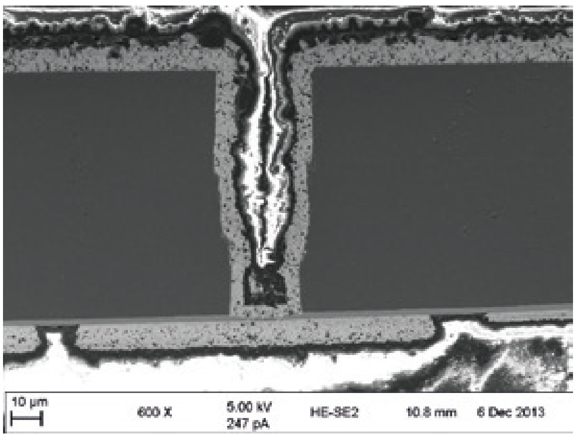
Today's industry standard in chip mounting technology is wire bonding. Wafers are metallized on their back side, diced, and then soldered to a chip carrier that also serves as a heat sink. Source, drain, and gate are now individually connected with bond wires. However, with rising operation frequency these bond wires act as an increasing inductive load. Introducing through substrate vias (TSV) offers an elegant way to reduce this load, minimize losses, and obtain better power efficiency. Such vias create an electrical connection of the front side of the wafer with its back side. During assembly one of the contacts, e.g. the source, is not connected with a bond wire, but by means of a TSV to the chip's back side and then to the ground. This reduces the number of bond wires needed, their inductive load, and also helps to optimize heat dissipation. However, this design evokes the challenge to process TSVs into the highly resistant SiC substrate.

The FBH has successfully developed a TSV process for 4-inch GaN on SiC wafers. The process is performed in the backend module after completing transistor processing. First, the wafers are cladded on the front with a bonding material and are temporarily bonded to a carrier wafer. This creates a wafer-carrier bond that is mechanically robust enough to allow the thinning of the wafer. A thinning step is necessary to facilitate the formation of TSVs by advanced inductively coupled plasma (ICP) etching and subsequent metallization. Furthermore, this process step allows to meet the impedance requirements and to match the height demands of the device package.

Bonding parameters and choice of carrier wafer material need careful consideration. This is due to the mismatch of coefficient of thermal expansion, resulting in strain and an undesired bow of the wafer-carrier system. Such bow is then transferred during the thinning process to the substrate wafer. WaferBOND® HT-10.10 temporary bonding material is deposited in a two-stage spin-coating process on the wafer, cured, and bonded at 180°C. The wafer can easily be removed from the carrier at 200°C. This process also protects air bridges of transistors on the front and withstands the SiC and AlGaN/GaN via etching steps.

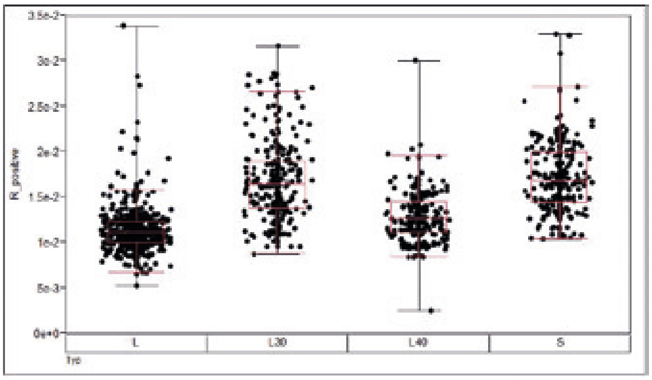
For thinning, a three-stage thinning process has been developed. To reach the target thickness of 100 µm, the wafer is lapped to about 180 µm thickness with 49 µm boron carbide grain. Then a pre-polish step with 9 µm boron carbide grain, followed by a final polishing step with 3 µm diamond grain are accomplished.

The via etch mask consists of an aluminum-indium tin oxide layer sequence. The SiC etch step is performed in an ICP single wafer etch chamber with a SF_6-He gas mixture. The etch time for the 100 µm thick SiC is about 3 hours. A 20 minutes chlorine-based GaN dry etch step follows.

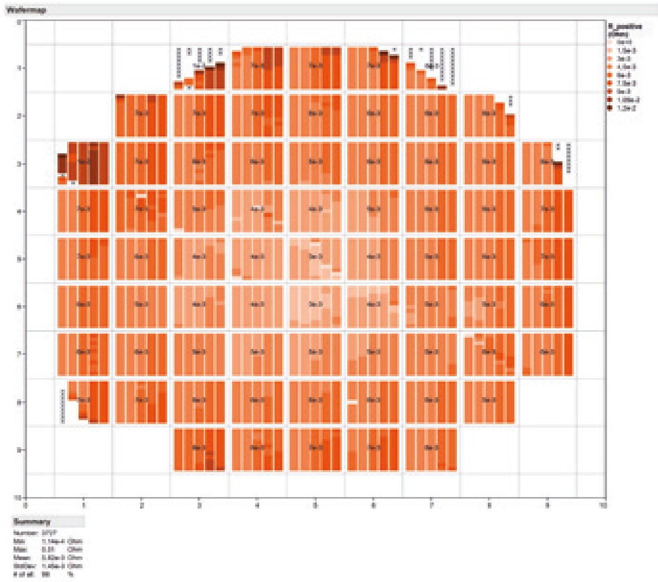


∧ **Fig. 1.** Cross section of a through substrate via after electroplating of gold.

The wafer-carrier bond faces challenging conditions during the two ICP etch processes. To reach reasonable etch rates especially for the SiC, the platen temperature should be as high as possible. But the stability of the temporary wafer bond material deteriorates when approaching 200°C, and the wafers tend to disintegrate. Debonding at elevated temperatures is promoted by strain due to the mismatch of the thermal expansion coefficients of wafer and carrier. In this trade-off between bond stability and etching rate we have carefully



∧ **Fig. 2.** Resistance (R_positive in mOhms) of TSV with different sizes: L= 60 µm, L30 = 30 µm, L40 = 40 mm, S = 20 µm.



∧ **Fig. 3.** Distribution of via resistance across a 4-inch GaN-on-SiC wafer.

adjusted the etch temperature, ICP plasma density, back side cooling, gas flows, and the design of the wafer chuck for repeatable high yield.

After removal of the etch mask and thorough cleaning of the via hole, a plating base consisting of titanium gold layers is deposited. To obtain a conformal metal liner for homogeneous electroplating, an evaporation tool with a long distance between metal source and wafer stack is used. Two evaporation steps under two different angles are executed. Fig. 1 shows a cross-section after the conformal liner has been reinforced by means of plating 5 µm gold from a gold electrolyte. Conformal metal distribution with good adhesion and contact to the front side metal is obtained. Fig. 2 shows that FBH's process allows to simultaneously form TSVs with a length of 80 µm and widths from 30 µm to 60 µm.

In conclusion, the carefully optimized overall process sequence for the formation of TSV in SiC is an essential precondition to simplify device packaging. It also opens up new prospects for designs and helps to further advance FBH's highly efficient high-power transistors for microwave devices.

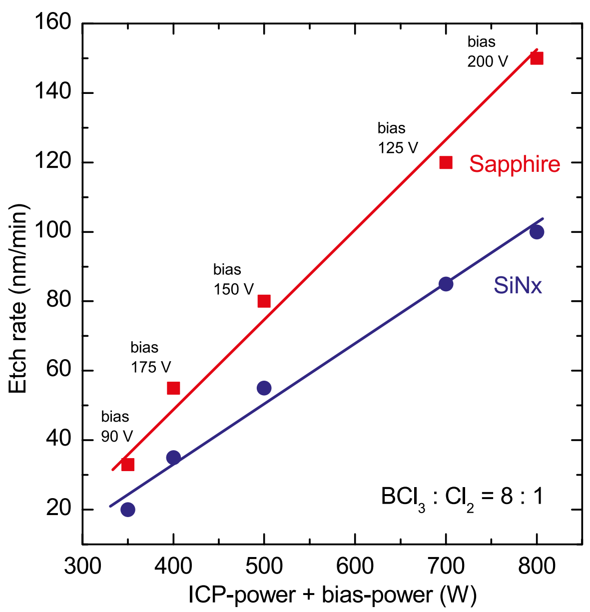
Um die Betriebsfrequenzen und die Leistungsdichte von modernen AlGaN/GaN-Transistoren weiter steigern zu können, müssen das elektrische Design und der Frontseitenprozess optimiert werden. Zugleich ist es notwendig, Rückseitenprozessierung und Aufbautechnik kontinuierlich weiter zu entwickeln. Ein wichtiger Schritt ist dabei, Durchkontaktierungen herzustellen, die Vorder- und Rückseite eines Siliziumkarbid (SiC)-Wafers elektrisch miteinander verbinden. Damit lassen sich Leitungsinduktivitäten senken und der Aufbauprozess vereinfachen. Das FBH hat einen darauf optimierten Prozess zur Herstellung dieser Durchgangskontakte in SiC entwickelt. Dabei wird, nachdem der SiC-Wafer temporär auf einen Stützwafer aufgeklebt wurde, das SiC auf eine Dicke von 100 µm abgedünnt und eine Ätzmaske aufgebracht. Diese wird anschließend in einem ICP-Ätzer geätzt. Nach der GaN-Plasmaätzung wird die Maske entfernt und eine Galvanikstartschicht aufgedampft, die mit einer galvanischen Goldabscheidung auf eine Dicke von 5 µm verstärkt wird.

Sapphire and AlN structuring for GaN/AlGaN ELOG templates

UV light emitting diodes (LED) are highly attractive for various applications and have the potential to replace, for example, mercury vapor lamps for UV water purification and UV curing of polymers. Accordingly, the epitaxial growth of GaN/AlGaN for light emitters in the ultra-violet (UV) spectral range has increasingly attracted interest in recent years. To improve the internal quantum efficiency of such LEDs, epitaxial layers with reduced dislocation densities are required. Epitaxial lateral overgrowth (ELO) on patterned sapphire substrates can help to reduce strain and dislocation density in GaN/AlGaN layers. Study of such effects requires a number of suitable pseudosubstrates (templates) with different pattern designs. At FBH, these templates are fabricated by photolithography and plasma etch processes. The patterned templates are processed on bare sapphire substrates as well as on sapphire covered with an AlN layer. Sapphire (Al_2O_3) and AlN belong to the hardest materials in semiconductor technology. They are resistant and extremely difficult to etch chemically, which makes patterning very challenging.

Because of properties like high aspect ratio imaging, vertical side-wall angle, and excellent dry-etch resistance, KMPR photoresist has been used as etch mask. Furthermore, SiN_x has been successfully applied as hard mask. Such etch masks allow to reach the desired etch depth of about 4 µm in c-plane sapphire. Honeycomb-like patterns or stripes were fabricated by i-line stepper lithography.

To create the desired textures in sapphire and/or AlN a highly anisotropic etch process is required. Reactive ion etching is the process of choice to produce such patterns with sufficient depth in sapphire substrates. Due to the high lattice energy of sapphire and AlN, high ion energies and ion densities are needed. An etching process with inductively coupled plasma (ICP) fulfills both requirements and is proven to be the best method for such patterning. The Sentech etch system SI 500 ICP has been used for patterning sapphire substrates with and without AlN layer. Chlorine-containing gases can be used as etchant for Al_2O_3 and AlN because volatile chlorides are formed. For etching metal oxides (e.g. Al_2O_3) it has been found that an excess of BCl_3 in a BCl_3/Cl_2 mixture facilitates relatively high etching rates.

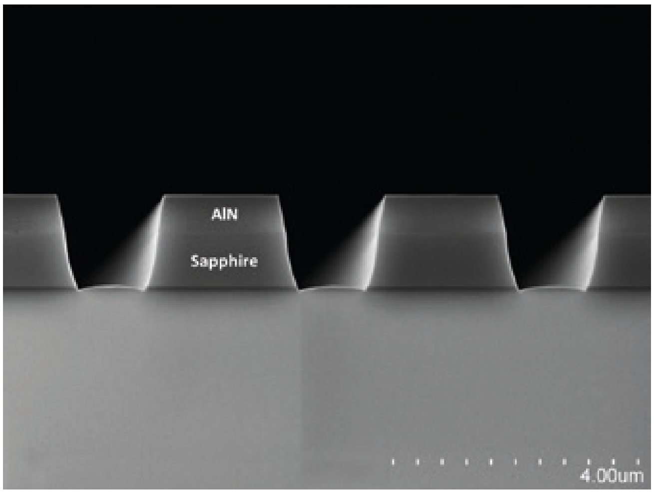


^ **Fig. 1.** Etch rates of sapphire and SiN_x as function of ICP and bias power.

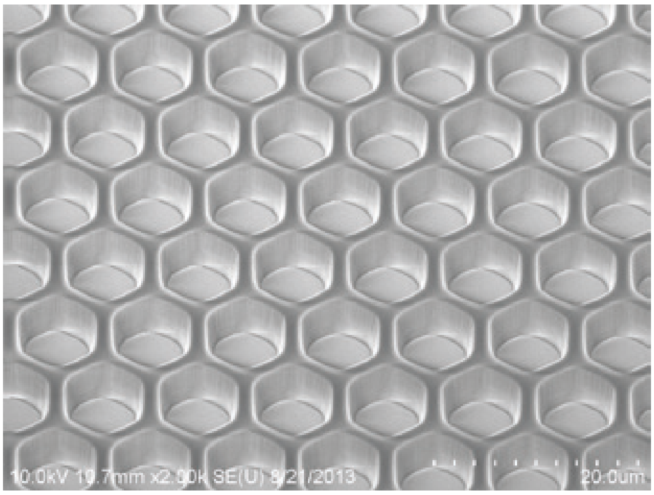
In the case of AlN etching, the situation is reverse, i.e., a high concentration of chlorine with a small content of BCl_3 is advantageous for etching. Our investigation showed that such high lattice energy materials like Al_2O_3 and AlN cannot be etched with only chlorine radicals, but presence of chlorine ions is essential. As a result, the etching process of sapphire and/or AlN is strongly anisotropic.

It has been found that the etch rate of the sapphire is proportional to the sum of ICP and bias power and can be controlled within a wide range as shown in Fig. 1. This means that the plasma density (influenced by ICP power) and the ion energy (influenced by bias power) determine the etch rate. Etch rate and etch selectivity have been optimized by varying gas flow ratio, RF power, and pressure.

Because of the limited thermal stability of the KMPR photoresist, the temperature of the wafer needs to be controlled during etching. Hence, the back side of the sapphire substrate is directly cooled with helium during plasma processing. Due to the limited layer thickness of KMPR, optimum etch conditions have been developed that ensure a sufficient etch selectivity between the KMPR etching mask and the Al_2O_3. An etch rate of sapphire of about 80 nm/min has been achieved with an etch selectivity of 1.5 to SiN_x and 0.75 to KMPR. AlN can be etched with an etch rate of 100 nm/min and an etch selectivity of 2 to SiN_x.



∧ **Fig. 2.** Dry etched AlN on patterned sapphire template.



∧ **Fig. 3.** Dry etched honeycomb-like structure of patterned sapphire template.

With these BCl_3/Cl_2-based ICP etch recipes, stripes with 4 µm depth, 6 µm width, and a pitch of 10 µm as well as honeycomb-like patterns, featuring a depth of 4 µm, a trench width of 4 µm, and a ridge width of 6 µm, have been fabricated. The etched surface is very smooth and free of residues. Due to the necessary ion bombardment, a slight trench is always formed. After wet-chemical removing the etch masks (KMPR or SiN_x) the final structures are ready for epitaxy (Figs. 2 and 3).

This work was partially supported by the Federal Ministry of Education and Research in the frame of the innovative regional growth core Berlin WideBaSe under contract no. 03WKBT01C as well as by the German Research Foundation (DFG) within the Collaborative Research Center 787.

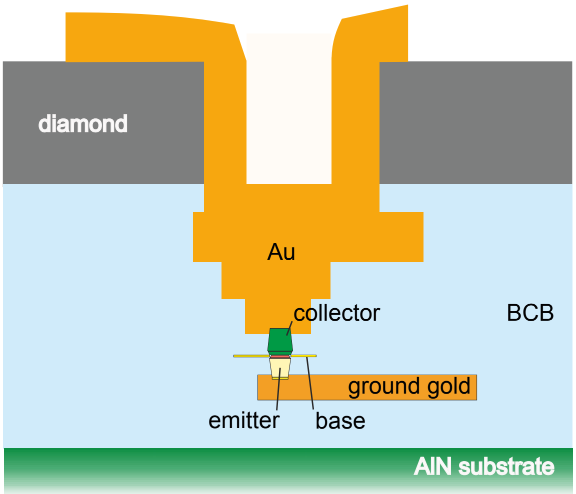
Um UV-Lichtemitter mit hoher Effizienz und Lebensdauer herzustellen, werden GaN-Schichten mit möglichst geringer Defektdichte benötigt. Eine Methode, die zu versetzungsarmen und verspannungsreduzierten GaN-Schichten führt, ist das laterale epitaktische Überwachsen (ELOG), beispielsweise von Saphir-Oberflächenstrukturen. Die dafür notwendigen strukturierten Saphir-Templates werden am FBH durch fotolithografische und Trockenätzprozesse hergestellt. Dazu wurde jeweils ein Strukturierungsprozess für AlN auf Saphir und für 4 µm tiefe Strukturen in Saphir entwickelt. Die Fotolackschichten werden mithilfe der Stepperlithografie hergestellt und dienen als Ätzmasken für die nachfolgenden chlorbasierten Trockenätzschritte (ICP-RIE). Auf diese Weise lassen sich unterschiedliche Oberflächen-Mikrostrukturen herstellen. Die so strukturierten Saphir-Wafer eignen sich ideal zum lateralen epitaktischen Überwachsen.

Publication

S. Hagedorn, E. Richter, U. Zeimer, D. Prasai, W. John, M. Weyers. “HVPE of $Al_xGa_{1-x}N$ layers on planar and trench patterned sapphire”, J. Cryst. Growth, vol. 353, no. 1, pp. 129-133 (2012).

Electroplating of gold via structures for an advanced transferred-substrate InP-HBT process

The outstanding material properties make indium phosphide (InP) hetero-bipolar transistors (HBTs) an object of extensive research and development of high-frequency transistors and associated power amplifiers. However, the benefits of such devices are still limited by self-heating during high-power, high-frequency operation. Thus, improved heat dissipation in the HBT periphery will push the performance limits with respect to speed and power. In our approach, a diamond layer (thermal conductivity of 600 - 800 W m^{-1} K^{-1} for thin layers) is bonded as heat spreader on top of the InP-HBTs by adhesive wafer bonding using benzocyclobutene-based polymers (BCB). Commercially available thin films of diamond grown by chemical vapor deposition (CVD) on 3" Si wafers have been used. The silicon substrate has to be removed from the CVD diamond after bonding. To circumvent the low thermal conductivity of BCB (0.29 W m^{-1} K^{-1}) vertical interconnects (vias) are established to create heat bridges (see Fig. 1). The vias should provide both thermal and electrical interconnects through the diamond layer to access active and passive elements embedded in the BCB stack. A technology is required to fabricate openings in the diamond/BCB stack that are terminated at the first metallization layer and need to be subsequently metallized. Dry etching processes to create holes through the diamond and BCB layers have been developed with oxygen and SF_6 as reactive gases. The electroplating process of gold was optimized using pulse plating.



∧ **Fig. 1.** Schematic cross-section of the HBT embedded in BCB with via interconnection.

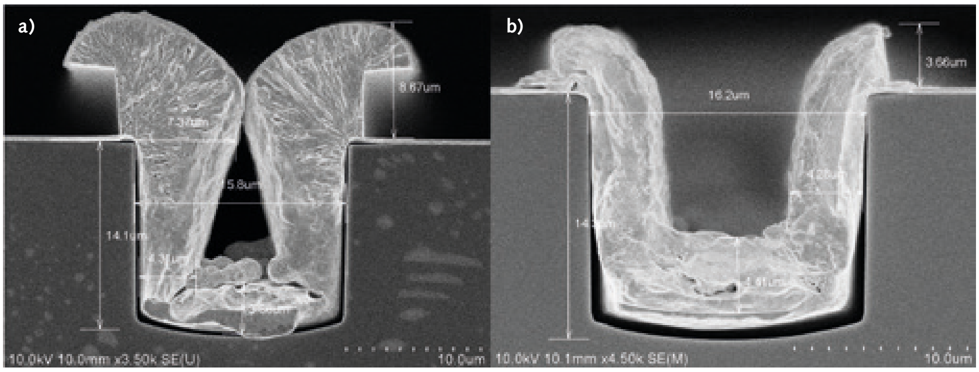
Electrical and thermal conduction requires homogeneous, conformal, and smoothly deposited metal in the vias. Proper operation of the high-frequency transistors and circuits requires low conductor and dielectric losses of interconnections and transmission lines. According to thermal simulations a gold thickness of about 3.5 µm in the vias is sufficient for improved heat dissipation. As a consequence of design rules, etch process and electromagnetic simulation vias with 15 µm diameter and 20 µm depth are targeted.

To save expensive substrates with CVD diamond layers, the development of deep via electroplating was performed on suitable test structures fabricated on GaAs wafers. The main goal of this investigation was to develop an electroplating process with the following criteria: conformal coverage of via's bottom and sidewalls as well as of the wafer surface in the vicinity of the hole, precise thicknesses control, low roughness, homogeneity on the wafer, and reproducibility from wafer to wafer.

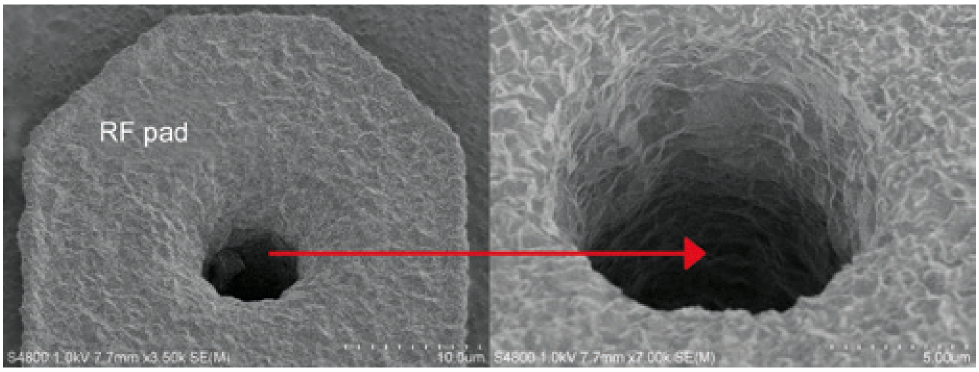
Potassium dicyanoaurate electrolyte was used for direct current (DC) electroplating and pulse plating. When filling vias by electroplating, the current density applied needs to be carefully adjusted according to the aspect ratio and to the relatively small area. This helps to ensure conformal coverage of the hole and avoid the formation of bigger grains. During electroplating in vias the metal ion concentration gets depleted at the via's bottom. This effect is relevant in DC electroplating, a technique with a permanent current flow between an anode and the substrate (cathode). With the so-called pulse plating technique it is possible to regenerate the depleted gold ion concentration closed to the surface of the substrate, i.e., also at the via's bottom. This technique uses an alternating current with pulse and pause. Pulse plating can improve layer properties compared to the direct current technique, i.e., higher electrical and thermal conductivity as well as lower roughness can be obtained at the same deposition time.

In our study, the electrolyte temperature, flow rate, current density, duty cycle (pulse and pause time), pulse current, and the layer thickness were varied. The results from DC plating demonstrate the strong influence of the current density on conformity and surface roughness. Using low current densities in the range of 1 mA/cm² it was possible to obtain a conformal gold layer, but the process time was significantly extended. An increase of electrolyte temperature from 40°C to 60°C led to conformal coverage. This is caused by a higher mobility of the gold ions. However, we observed a degradation of homogeneity of the gold thickness on the wafer at higher temperature. A huge improvement of roughness, homogeneity, and conformity was achieved with the pulse plating technique. Applying an average current density of 0.5 mA/cm² and a small duty cycle of 1:4 pulse/pause led to the desired effect. The results obtained with GaAs test wafers were successfully applied to processing of InP-HBTs transferred to CVD diamond (see Fig. 3).

Part of the work is funded by the German Federal Ministry of Education and Research within the project "AVTE" under reference No. 16V0060.



∧ **Fig. 2.** Scanning electron micrographs of cross-sections of vias after electroplating a) standard electroplating process with DC plating, b) optimized pulse plating process.



∧ **Fig. 3.** Scanning electron micrographs of RF pad with via (left) and detailed view of the sidewall showing conformal coverage (right).

Mit InP-basierten Bauelementen lassen sich gleichzeitig hohe Frequenzen und hohe Leistungen erzielen. Allerdings begrenzt die entstehende Abwärme die Leistungsfähigkeit und erfordert besondere Maßnahmen zur Wärmeableitung. Der hier beschriebene Ansatz verwendet dazu Diamant-Substrate. Dabei ermöglichen vertikale Kontaktverbindungen (Vias) die Wärmeableitung und elektrische Kontaktierung. Die Parameter zur elektrochemischen Gold-Abscheidung für Via-Strukturen wurden untersucht und optimiert. Mittels Pulsstromabscheidung konnte eine homogene, konforme und reproduzierbare Goldabscheidung erreicht werden. Diese wurde als neuer Standard für die Abscheidung in Via-Strukturen etabliert.

Publication

K. Nosaeva , W. John, N. Weimann, O. Krüger, T. Krämer, "Development of a Via Etch Process through Diamond and BCB for an Advanced Transferred-Substrate InP-HBT Process", 37th Workshop on Compound Semiconductor Devices and Integrated Circuits (WOCSDICE), Warnemünde, Germany, May 26-29, ISBN 978-3-00-041435-0, pp. 23-24, (2013).

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