Leibniz
Ferdinand
Braun
Institut

Annual Report
Jahresbericht
2015

Annual Report
Jahresbericht
2015

Every time and society has its own special demands that are resolved by social interactions and technological developments. Current challenges we have to face include: How can we use our resources more responsibly with the help of environmentally-friendly energy? How to preserve health and well-being within an ageing population? How to meet the challenges of an increasingly digitized society with the appropriate information and communication technologies? Technical developments like those provided by the Ferdinand-Braun-Institut considerably contribute to find matching solutions, thus safeguarding prosperity and quality of life of human beings also in the future.

FBH develops, for example, digital GaN power amplifiers for next-generation mobile communication systems – the last missing building block on the way to the completely digital transmitter. These devices are highly capable and improve efficiency at the same time. Therefore, they are ideally suited for the demanding requirements that are to be met by 5G mobile networks, the future communication standard following LTE.

For applications in medical technology, the FBH develops diode lasers with tailored properties. They are used, among others, in photodynamic cancer therapy where tumor cells are enriched with a medication during treatment. When light of a precisely defined wavelength hits the cells, it activates the active agent and the afflicted cells are destroyed. Also in the HautScan project, terminated in 2015, in which the FBH closely cooperated with the Charité, a very compact light source has been developed. This source uses Raman spectroscopy to prematurely detect a heavy adverse effect of the chemotherapeutic Doxorubicin used in cancer therapy so that therapists can actively counteract in due time.

Not only in HautScan, but in practically all projects, FBH closely cooperates with other research institutions, universities, and industrial partner to ensure research and development at the highest level. Collaboration with different universities in the region and throughout Germany has been consolidated within the frame of joint labs.

Eventually, FBH produces results which are unique in many cases and are acknowledged internationally since almost 25 years. What is the key to our success? Besides scientific excellence, we distinguish ourselves by the particularly close cooperation with industry since we collaborate already during the development phase tightly with these partners. This way, we ensure that our results are transferred into application as rapidly as possible. We will continue this path also in the future, even more since our results confirm our success: TRUMPF, which is another important industrial partner after JENOPTIK, has settled in close vicinity to the institute. Since 2015, the world-wide leading laser manufacturer is represented in Berlin at the Adlershof location with its own branch office. We also started increasingly to advance our diode lasers, from the laser chips to the modules to the final systems which can be used by companies for testing in their own applications. In this regard, the Prototype Engineering Lab established two years ago already yielded several prototypes.

The Advanced UV for Life consortium, funded by the German Federal Ministry of Education and Research, also shaped up well; recently we succeeded to get with Osram a major industrial partner on board. Osram has a high economic interest to gain access to top-quality UV light-emitting diodes in substantial quantities in order to market them in various applications. The company is now one of more than 35 partners of the consortium that joined forces along the whole value chain of UV LED development, aiming to make them available for a broad market of users.

In the year after its excellent evaluation, FBH has continued to develop positively. The amount of projects annually processed at FBH has increased by 5 % to almost 200 – even though the number of staff remained stable. I therefore express my gratitude to the employees at Ferdinand-Braun-Institut. They ensure with their knowledge and dedication that more and more projects can be handled on the highest level.

Looking at the figures also reveals that our budget has been rising since many years, slowly but steadily. Owing to the financial means that are provided by federal funds from the Pact for Research and Innovation, our basic funding increases by 3 % annually. We like to thank our federal and state authorities for providing us generously with financial resources, thus enabling us to finance the very costly operation of our cleanroom facilities. However, these means can hardly cover the steadily rising costs for energy, consumables, and personnel. As a result, we are confronted with a foreseeable structural budget deficit, thus hampering to make urgently required investments. Yet, they are necessary in order to remain competitive on an international level – for new procurement of equipment on the current technical level and the like. Hence, we are facing challenges for the FBH that we need to find solutions for.

At the same time, almost 50 % of our overall budget comes from third-party funding. The high share reflects the strong international acceptance and the high demand from industry. This is both a blessing and a curse, since a lot of highly qualified co-workers can only be employed temporarily, related to specific projects. Training in a high-tech area like ours, however, takes a long time and requires comprehensive experience – und is thus a precondition to achieve excellent results. The current regulations on time-limited contracts for high-technology institutes such as ours are anything but helpful. Our success depends on specialized experts whom we need to recruit and retain on a long-term basis. We will therefore seek dialogue with our funding authorities, promoting better structural parameters preventing stumbling blocks in our so far successful path.

So, prospects are exciting, not only regarding our R&D results. I am looking forward to the fruitful exchange with all of you, within our team, and for many stimulating developments in the ongoing year. I am also hoping that you enjoy reading through our results achieved in 2015.

Yours sincerely,

Günther Tränkle

Günther Tränkle

Jede Zeit und Gesellschaft hat ihre eigenen Erfordernisse, die im sozialen Miteinander und mithilfe technologischer Entwicklungen gelöst werden. Zu unseren aktuellen Herausforderungen zählen: Wie können wir unsere Ressourcen mit umweltfreundlicher Energie verantwortungsbewusster nutzen, wie die Gesundheit und das Wohlbefinden einer alternden Bevölkerung erhalten und den Herausforderungen einer zunehmend digitalen Gesellschaft mit dazu passenden Informations- und Kommunikationstechnologien begegnen? Technische Lösungen, wie sie unter anderem am Ferdinand-Braun-Institut entwickelt werden, leisten hierbei einen wesentlichen Beitrag, der den Wohlstand und die Lebensqualität von uns Menschen auch zukünftig sichert.

So entwickelt das FBH beispielsweise digitale GaN-Leistungsverstärker für mobile Kommunikationssysteme der nächsten Generation – der letzte noch fehlende Baustein auf dem Weg zu einem komplett digitalen Transmitter. Sie sind leistungsfähiger und verbessern zugleich die Energieeffizienz. Damit eignen sie sich ideal für die hohen Anforderungen an die 5G-Mobilfunknetze als LTE-Nachfolger.

Für die Medizintechnik entwickelt das FBH Diodenlaser mit maßgeschneiderten Eigenschaften. Sie werden etwa in der fotodynamischen Therapie eingesetzt, indem sie bei einer exakt definierten Wellenlänge ein in Tumorzellen angereichertes Medikament aktivieren – die befallenen Zellen werden zerstört. Oder im 2015 abgeschlossenen Projekt HautScan, bei dem das FBH eng mit der Charité kooperierte. Dabei wurde eine sehr kompakte Lichtquelle entwickelt, die die Raman-Spektroskopie nutzt, um bei der Krebsbehandlung künftig frühzeitig und vor Ort eine schwere Nebenwirkung des Chemotherapeutikums Doxorubicin zu erkennen und rechtzeitig entgegenzusteuern.

Nicht nur bei HautScan, sondern in praktisch allen Projekten kooperiert das FBH eng mit anderen Forschungseinrichtungen, Universitäten und Industriepartnern, um Forschung und Entwicklung auf höchstem Niveau zu sichern. Die Zusammenarbeit mit mehreren Hochschulen in der Region und bundesweit hat das FBH auch im Rahmen von Joint Labs verstetigt.

Im Ergebnis entstehen am FBH seit fast 25 Jahren Ergebnisse, die vielfach einzigartig sind und international wahrgenommen werden. Was macht unseren Erfolg aus? Neben wissenschaftlicher Exzellenz, zeichnen wir uns besonders durch die enge Zusammenarbeit mit Unternehmen aus, denn wir kooperieren bereits während der Entwicklung eng mit Partnern aus der Industrie. Damit stellen wir sicher, dass unsere Ergebnisse möglichst rasch in die Anwendung kommen. Diesen Weg werden wir auch künftig weiter beschreiten. Die Ergebnisse bestätigen unseren Erfolg, zumal sich mit TRUMPF nach JENOPTIK erneut ein wichtiger Industriepartner in unmittelbarer Institutsnähe angesiedelt hat. Seit 2015 ist der weltweit führende Laserhersteller mit einer eigenen Niederlassung nun in Berlin am Standort Adlershof vertreten. Zusätzlich entwickeln wir unsere Diodenlaser zunehmend von Laserchips über Module bis hin zu fertigen Systemen, die von Unternehmen direkt in den eigenen Anwendungen getestet werden können. Das vor zwei Jahren geschaffene EntwicklungsZentrum ist hierbei ein wichtiger Baustein, der bereits mehrere Prototypen hervorgebracht hat.

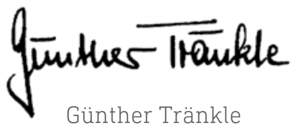
Auch in dem vom FBH geleiteten Zwanzig20-Vorhaben Advanced UV for Life ist es uns gelungen, Osram als großen Industriepartner an Bord zu holen. Osram hat ein hohes wirtschaftliches Interesse an der Verfügbarkeit hochwertiger UV-Leuchtdioden, um diese in vielfältigen Anwendungen zu vermarkten. Das Unternehmen ist nun einer von mehr als 35 Partnern im Konsortium entlang der gesamten Wertschöpfungskette bei der Entwicklung von UV-LEDs, um diese für einen breiten Markt verfügbar zu machen.

Im Jahr nach seiner exzellenten Evaluierung hat sich das FBH jedenfalls weiter positiv entwickelt. Die Anzahl der am FBH jährlich bearbeiteten Projekte ist bei gleichbleibendem Personalbestand von 2014 auf 2015 erneut um 5 % auf fast 200 laufende Projekte angestiegen. Mein Dank gilt daher ganz besonders den Mitarbeiterinnen und Mitarbeitern am Ferdinand-Braun-Institut, die mit ihrem Wissen und ihrem Engagement sicherstellen, dass immer mehr Projekte auf hohem Niveau durchgeführt werden können.

Ein Blick auf die Zahlen zeigt auch, dass unser Budget seit vielen Jahren langsam, aber stetig gestiegen ist. Dank der finanziellen Mittel, die über den Pakt für Forschung und Innovation bereitgestellt werden, steigt unsere Grundfinanzierung um jährlich 3 %. Für diese großzügige Förderung danken wir unseren Zuwendungsgebern aus Bund und Land, die damit die Finanzierung des laufenden und sehr kostenintensiven Reinraumbetriebs ermöglichen. Jedoch können diese Mittel die stetig steigenden Kosten für Energie, Verbrauchsmittel und Personal inzwischen nicht mehr auffangen. Damit rutschen wir absehbar in eine strukturelle Unterfinanzierung, die es uns nicht mehr erlaubt dringend notwendige Investitionen zu tätigen. Diese sind jedoch notwendig, um weiter international wettbewerbsfähig zu sein – etwa für Neuanschaffungen von Geräten auf dem neuesten technischen Stand, die veraltetes Equipment ersetzen sollen. Damit warten in den nächsten Jahren Herausforderungen auf das FBH, für die wir eine Lösung finden müssen.

Zugleich stammen fast 50 % unseres Gesamtetats aus Drittmitteln. Dieser hohe Anteil spiegelt den starken internationalen Zuspruch und die hohe Nachfrage aus der Industrie wider. Das ist Fluch und Segen zugleich, denn dadurch können viele hoch qualifizierte Mitarbeiterinnen und Mitarbeiter nur über Projekte zeitlich befristet beschäftigt werden. Die Ausbildung in einem Hightech-Bereich wie dem unseren dauert jedoch lange und erfordert umfassende Erfahrungen, um exzellente Ergebnisse erzielen zu können. Insofern sind die aktuellen Befristungsregelungen für Institute unseres Zuschnitts, die Know-how-Träger benötigen und langfristig an sich binden müssen, alles andere als hilfreich. Wir werden daher den Dialog mit unseren Zuwendungsgebern suchen, um für bessere strukturelle Rahmenbedingungen zu werben, die uns keine Stolpersteine in unseren bislang so erfolgreichen Weg legen.

Es bleibt also nicht nur im Hinblick auf unsere Entwicklungen spannend. Ich freue mich auf den fruchtbaren Austausch mit Ihnen allen, im Team und auf viele inspirierende Entwicklungen im laufenden Jahr. Ein anregende Lektüre der Ergebnisse aus dem Jahr 2015 wünscht Ihnen, Ihr



Günther Tränkle

Table of contents
Inhaltsverzeichnis

Profile
Profil

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

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

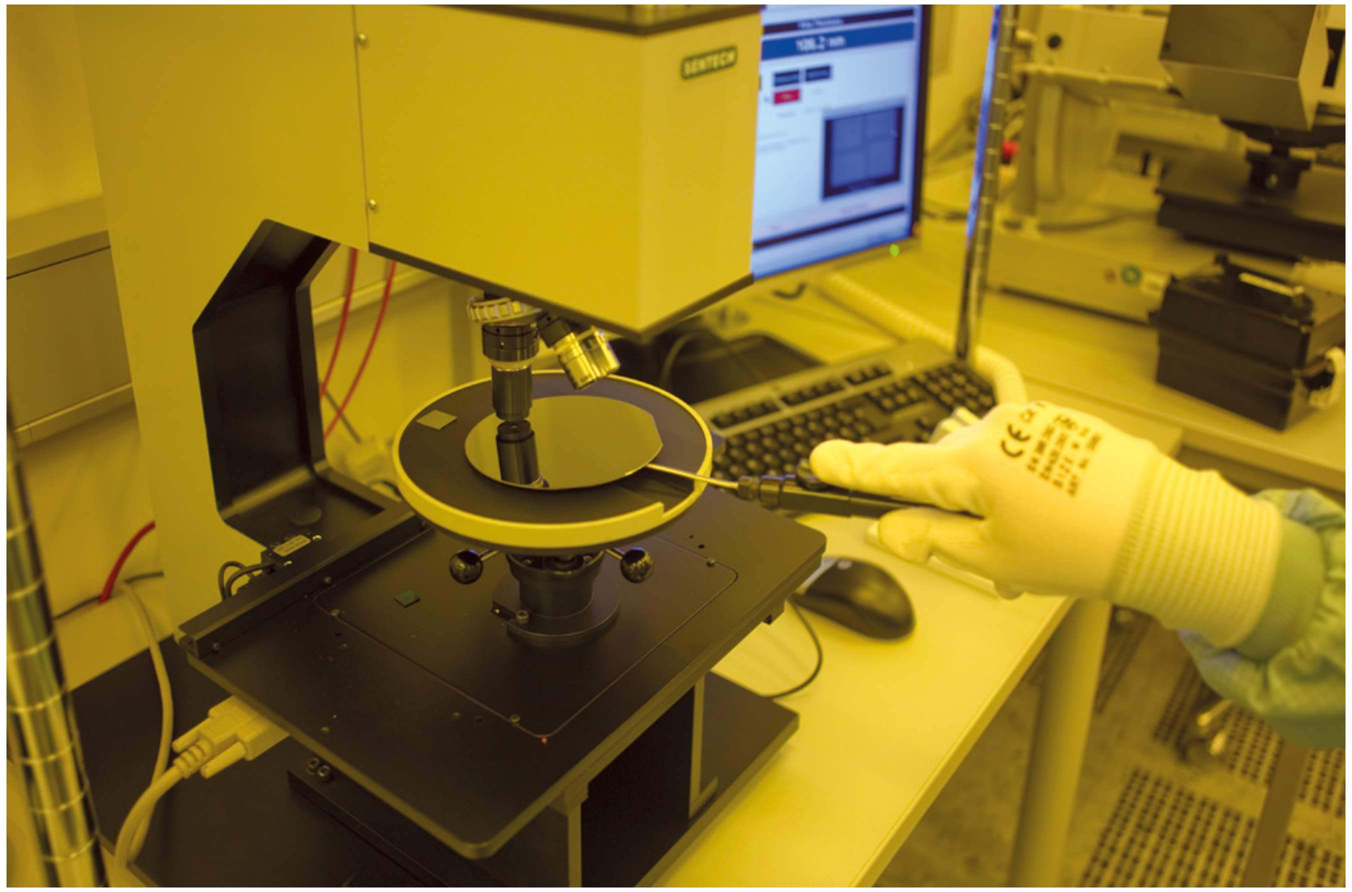
Das FBH im Profil

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. Darüber hinaus entwickelt es Lasertreiber sowie kompakte atmosphärische Mikrowellenplasmaquellen mit Niederspannungsversorgung für vielfältige Anwendungen.

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.
- We work closely cross-linked with the scientific community – including university cooperations (joint labs), strategic networks, and international projects.
- 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.

Profile Profil

Leitbild

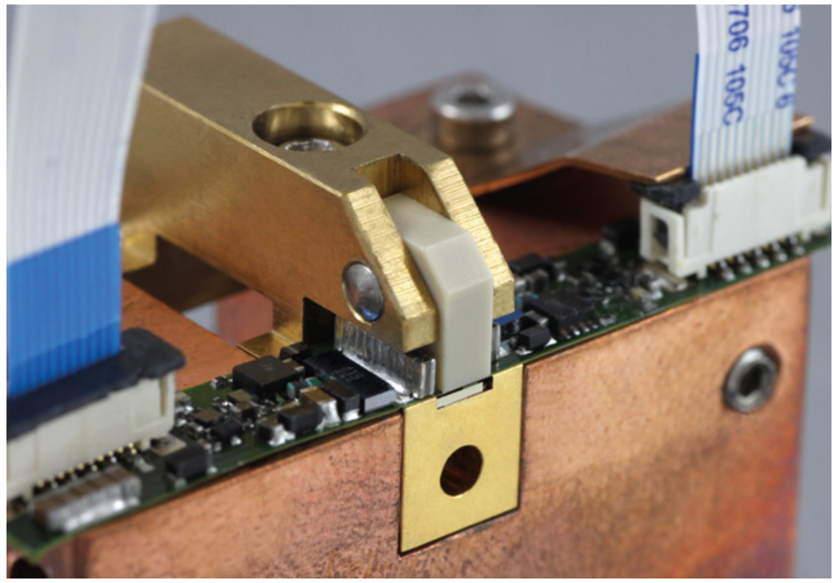
... translating ideas into innovations

- 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 arbeiten eng vernetzt mit der Scientific Community: im Rahmen von Hochschulkooperationen (Joint Labs), strategischen Verbünden und in internationalen Projekten.
- 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.

Research topics & competencies

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.



Photonics
- high-power diode lasers: broad area & bars
- high-brightness & narrowband diode lasers
- hybrid laser modules (cw & pulsed): from NIR to UV spectral range, e.g. for displays, laser sensors, laser metrology, ...
- nitride laser diodes for the blue & UV spectral range
- short-wave UV LEDs, e.g. for sensors, disinfection, medical & production technology, ...

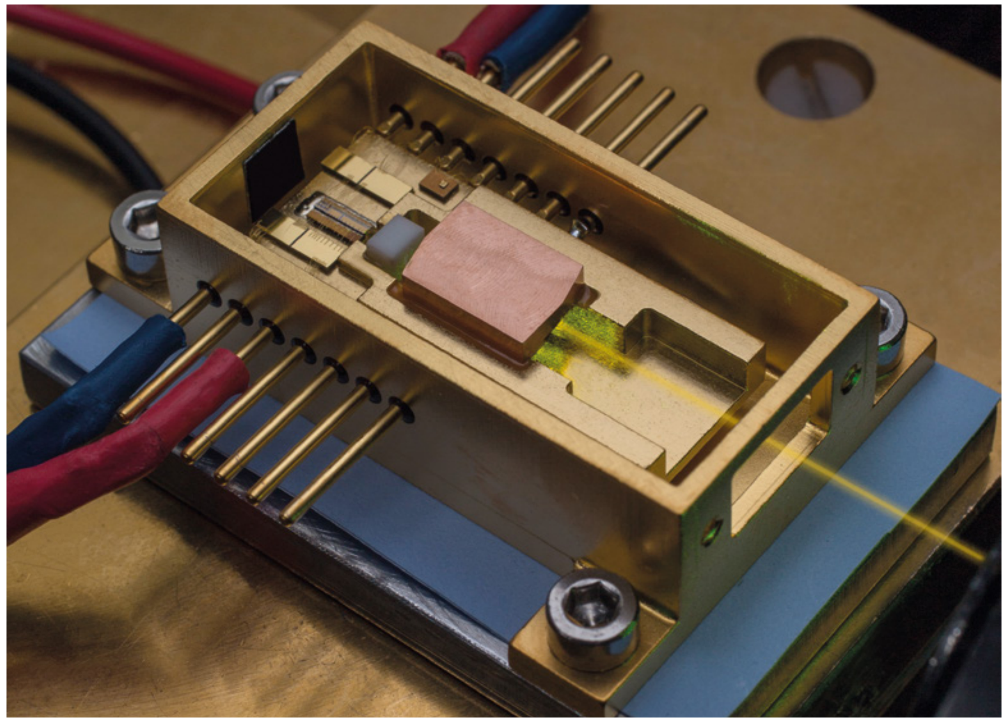
III-V Electronics
- GaN microwave transistors & MMICs
- advanced power amplifier concepts for the wireless infrastructure
- integrated circuits with InP HBTs for the 100...500 GHz frequency range
- fast drivers for laser diodes
- GaN power electronics

III-V Technology
- epitaxy (MOVPE) of GaAs- & GaN-based layer structures for devices
- (Al)GaN HVPE for bulk crystal growth
- in-situ control techniques for MOVPE & HVPE
- complete process line 2" - 4" for GaAs, InP, SiC & GaN devices, including laser micro processing
- InP HBT technology for mm-wave & THz applications, hetero-integrated SiGe-BiCMOS/InP-HBT foundry (SciFab) with IHP
- mounting & assembling

Science Management
- technology transfer & marketing
- education & training management

Forschungsthemen & Kompetenzbereiche

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.



Photonik
- Hochleistungs-Diodenlaser: Breitstreifen & Barren
- Hochbrillante & spektral schmalbandige Diodenlaser
- Hybride Lasermodule (CW & gepulst): NIR bis UV-Spektralbereich, u.a. für Displays, Lasersensorik, Lasermetrologie, ...
- Nitrid-Laserdioden für den blauen & UV-Spektralbereich
- Kurzwellige UV-Leuchtdioden, u.a. für Sensorik, Desinfektion, Medizin- und Produktionstechnik, ...

III/V-Elektronik
- GaN-Mikrowellentransistoren & -MMICs
- Neue Leistungsverstärkerkonzepte für die drahtlose Infrastruktur
- Integrierte Schaltungen mit InP-HBTs für den Frequenzbereich 100...500 GHz
- Schnelle Treiber für Laserdioden
- GaN-Leistungselektronik

III/V-Technologie
- Epitaxie (MOVPE) von GaAs- & GaN-basierten Schichtstrukturen für Bauelemente
- (Al)GaN-HVPE für Volumenkristalle
- In-situ Kontrolltechniken bei MOVPE & HVPE
- Komplette Prozesslinie 2" - 4" für GaAs-, InP-, SiC- & GaN-Bauelemente inklusive Lasermikrostrukturierung
- InP-HBT-Technologie für Millimeterwellen- & THz-Anwendungen, heterointegrierter SiGe-BiCMOS-/InP-HBT-Foundryprozess (SciFab) mit dem IHP
- Aufbau- & Verbindungstechnik

Wissenschaftsmanagement
- Technologietransfer & Marketing
- Bildungsmanagement

Contact
Kontakt

Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik im Forschungsverbund Berlin e.V. Gustav-Kirchhoff-Str. 4 12489 Berlin, Germany	Phone +49.30.6392-2600 Fax +49.30.6392-2602 Email fbh@fbh-berlin.de Web www.fbh-berlin.de
Director Direktor	Prof. Dr. rer. nat. Günther Tränkle Phone +49.30.6392-2601 guenther.traenkle@fbh-berlin.de
Assistant to the Director Referentin der Institutsleitung	Doreen Friedrich, M.Sc., Dipl.-Ing. (FH) Phone +49.30.6392-3391 doreen.friedrich@fbh-berlin.de
Science Management Wissenschaftsmanagement	Nicolas Hübener, M.Sc., Dipl. Kfm. (FH) Phone +49.30.6392-3396 nicolas.huebener@fbh-berlin.de
Kommunikation Communications	Petra Immerz, M.A. Phone +49.30.6392-2626 petra.immerz@fbh-berlin.de

Central Contact for Research Areas
Fachliche Ansprechpartner für die Forschungsbereiche

Photonics Photonik	Prof. Dr. rer. nat. Günther Tränkle Phone +49.30. 6392-2601 guenther.traenkle@fbh-berlin.de
III-V Electronics III/V-Elektronik	Deputy Director Stellvertretender Direktor Prof. Dr.-Ing. Wolfgang Heinrich Phone +49.30.6392-2620 wolfgang.heinrich@fbh-berlin.de
III-V Technology III/V-Technologie	Prof. Dr. rer. nat. Markus Weyers Phone +49.30.6392-2670 markus.weyers@fbh-berlin.de

Forschungsverbund Berlin e.V.

The Forschungsverbund Berlin e.V. represents 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 maintaining 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 are member of 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.

Forschungsverbund Berlin e.V.
Rudower Chaussee 17
12489 Berlin, Germany
Phone +49.30.6392-3330
Fax +49.30.6392-3333
Email urban@fv-berlin.de
Web www.fv-berlin.de

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 administrative Infrastruktur (Verbundverwaltung, Geschäftsführerin Dr. Manuela Urban) und sind Mitglied der 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

	2014	2015
Staff / **Team**	290	290
Scientists / Wissenschaftlerinnen & Wissenschaftler	96	100
PhD students / Promovierende	49	52
Student assistants & bachelor/master students / Studentische Hilfskräfte & Bachelor-/Masterstudierende	35	25
Trainees / Auszubildende	9	8
Projects / **Laufende Projekte**	183	192
Publications (peer reviewed) / **Publikationen (referiert)**	87	102
Patents / **Patente**	203	210
Talks (invited) / **Vorträge (eingeladene)**	158 (23)	167 (28)
Budget (in million Euros) / **Umsatz (Mio. Euro)**		
Basic funding: State of Berlin and Federal Government / Grundfinanzierung durch das Land Berlin und den Bund	12,6	13,3
Public project funding / Öffentliche Drittmittel	8,9	9,8
Industrial contracts / Industrielle Auftragsforschung	1,7	2,7

2014
2015

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
Managing 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

III-V Electronics

Microwave Department
Prof. Dr.-Ing. W. Heinrich
- Electromagnetic Simulation
- Measurements
- Circuit Design
- Microplasmas & Laser Drivers

III-V Electronics Labs
- **RF Power** – *O. Bengtsson, PhD*
- **Digital PA** – *Dr.-Ing. A. Wentzel*
- Joint Lab **BTU-CS – FBH Microwave** – *Prof. Dr.-Ing. M. Rudolph* (BTU-CS)
- Joint Lab **THz Components & Systems** – *Prof. Dr. V. Krozer (FBH & Goethe-Uni Frankfurt)*
- **GaN Microwave Devices** – *Dr.-Ing. J. Würfl*

Power Electronics Department
Dr.-Ing. J. Würfl
- Measurements
- Reliability

- **GaN Power Electronics Devices** – *Dr. O. Hilt*
- Joint Lab **Power Electronics** – *Dr.-Ing. J. Würfl / Prof. Dr.-Ing. S. Dieckerhoff* (TU Berlin)

Photonics

Optoelectronics Department
Dr.-Ing. A. Knigge
- Chip Design
- Chip Technology
- Laser Measurements

Photonics Labs
- **High-Power Diode Lasers** – *P. Crump, PhD*
- **Laser Modules** – *Dr. K. Paschke*
- **Laser Sensors** – *PD Dr. B. Sumpf*
- Joint Lab **Laser Metrology** – *Dr. A. Wicht / Prof. Dr. A. Peters* (HU Berlin)
- Joint Lab **GaN Optoelectronics** – *Dr. S. Einfeldt / Prof. Dr. M. Kneissl* (TU Berlin)

III-V Technology

Materials Technology Department
Prof. Dr. M. Weyers
- Arsenides & Phosphides
- Nitrides
- Material Analytics

III-V Technology Labs

Process Technology Department
Dr. O. Krüger
- Frontend
- Backend

InP Devices & SciFab – *N. Weimann, PhD*

Mounting & Assembly Department
Dr. S. Knigge
- Laser Diodes
- Light-Emitting Diodes
- Microwave Devices

Prototype Engineering – *U. Winterwerber*

effective / Stand 31.12.2015

Scientific advisory board
Wissenschaftlicher Beirat

Chair Vorsitz

Dr. Ulf Meiners
United Monolithic Semiconductors, Ulm

Members Mitglieder

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

Prof. Dr.-Ing. Manfred Berroth
Universität Stuttgart

Prof. Dr.-Ing. Wolfgang Bösch
Technische Universität Graz (A)

Dr. Thomas Fehn
SPI Lasers, Southampton (UK)

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

Dr. Patrick Scheele
Airbus Defence & Space, Ulm

Dr.-Ing. Christian Schmitz
TRUMPF Laser- & Systemtechnik GmbH, Ditzingen

Berry Smutny
DELOS Space GmbH, Frankfurt am Main

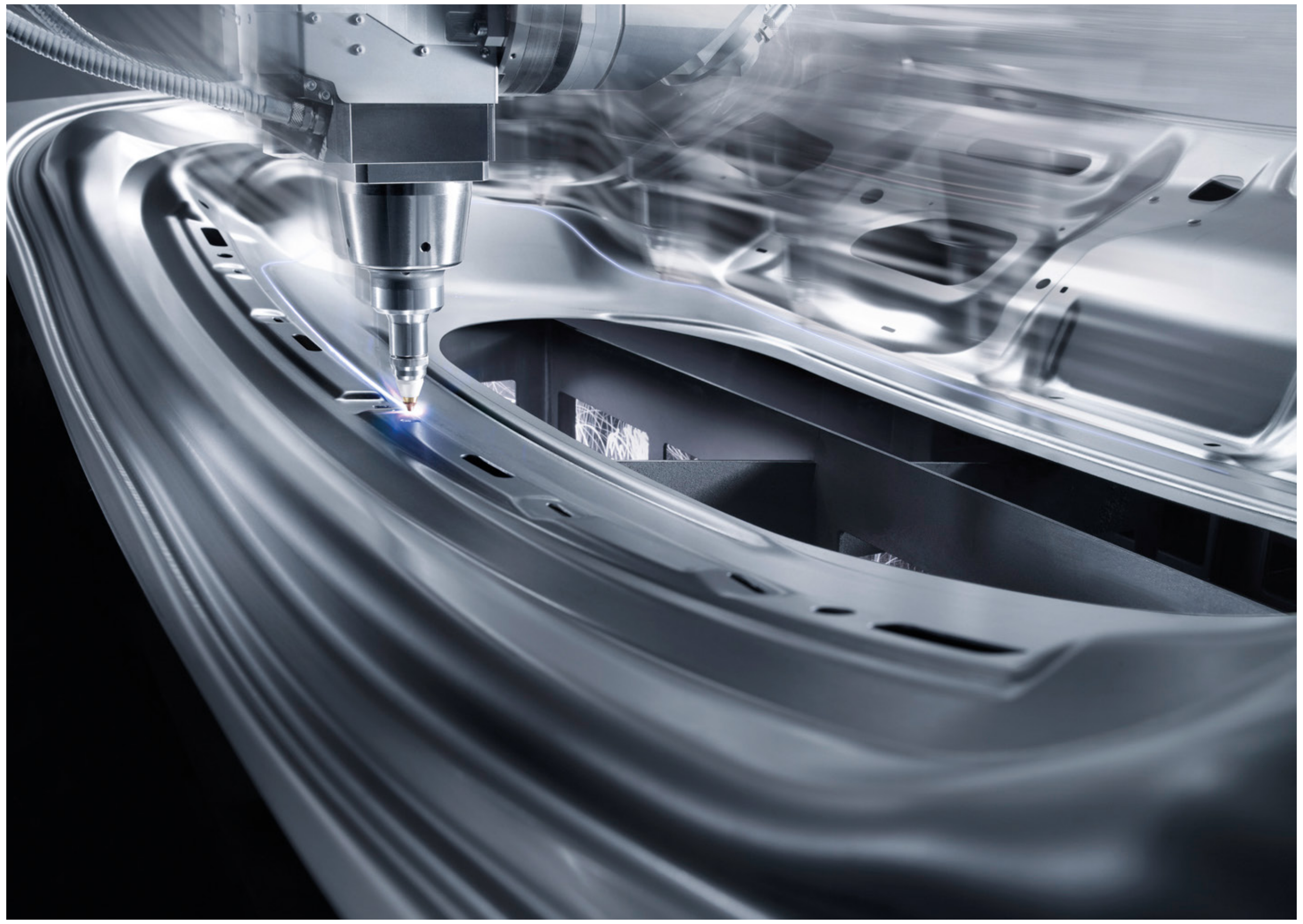
Dr. Ulrich Steegmüller
Osram Opto Semiconductors GmbH, Regensburg

Prof. Dr.-Ing. Stephan Völker
Technische Universität Berlin

Prof. Jelena Vuckovic
Stanford University (USA)

Highlights
Schlaglichter

Closer to the research partner FBH – TRUMPF opens subsidiary for laser diodes



Diode-pumped solid-state lasers have long been an indispensable tool in automotive production. Diodengepumpte Festkörperlaser sind aus der Automobilproduktion nicht mehr wegzudenken.

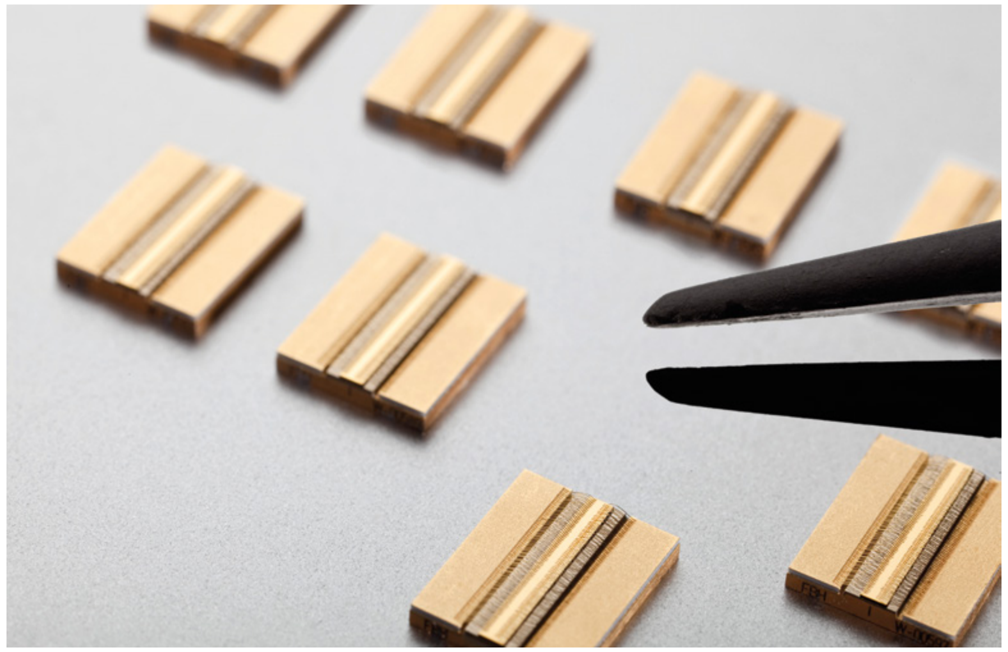
Once more, one of FBH's important long-term industrial partners has settled in close vicinity to the institute. In October, world-wide leading laser manufacturer TRUMPF has set-up a new subsidiary for the advance engineering of laser diodes in Berlin, currently employing a staff of ten people. This way, the company wants to continue expanding its technological and market lead in the high-performance diode laser sector. The close cooperation between industry and research is aimed at making laser systems from TRUMPF even more energy-efficient.

The group cooperates particularly close with FBH's High-Power Diode Lasers Lab specialized in high-performance diode lasers for pumping of solid-state lasers and for direct application in materials processing and medicine. As a result, crucial expertise remains firmly established in the region. TRUMPF and FBH have already worked for several years now on brilliant high-power lasers, including PhD positions at FBH that are funded by the company. "Over the past years our research activities have resulted in numerous patents, enabling further improvements to diode lasers," says FBH's Director Günther Tränkle. "The demand is there and will continue to grow, because the market for laser systems that can process and cut metals is vast." For some materials, such as the tempered steel used in the manufacture of monocoque safety cells in automobiles, the laser is virtually unrivaled and has long since become an indispensable tool in production.

In terms of power density and power-to-light conversion rate, diode lasers from FBH and TRUMPF are currently among the most powerful in the world, and new records are constantly being set in the laboratories. The Berlin TRUMPF subsidiary – which is not only well positioned in the fields of semiconductor laser physics, mounting technology, design, and simulation but also has its own cleanroom facilities – will be driving the development further.

Näher am Forschungspartner FBH – TRUMPF-Niederlassung in Berlin eröffnet

Erneut hat sich ein wichtiger und langjähriger Industriepartner des Ferdinand-Braun-Instituts in unmittelbarer Nähe zum Institut angesiedelt. Der weltweit führende Laserhersteller TRUMPF hat im Oktober eine neue Niederlassung für die Vorausentwicklung von Laserdioden in Berlin mit zurzeit zehn Mitarbeiterinnen und Mitarbeitern gegründet. Damit will das Unternehmen seine Technologie- und Marktführerschaft bei Hochleistungs-Diodenlasern weiter ausbauen. Durch die enge Zusammenarbeit von Industrie und Forschung sollen die Lasersysteme von TRUMPF noch energieeffizienter werden.



These diode lasers deliver high efficiency and high optical output power at the same time and are therefore ideally suited for laser materials processing.
Diese Diodenlaser liefern zugleich hohe Effizienz und hohe optische Ausgangsleistung. Damit eignen sie sich ideal für die Lasermaterialbearbeitung.

Die Gruppe kooperiert besonders eng mit dem High-Power Diode Lasers Lab des FBH, das sich auf Hochleistungs-Diodenlaser zum Pumpen von Festkörperlasern und für den direkten Einsatz in der Materialbearbeitung und der Medizin spezialisiert hat. Wichtiges Know-how bleibt so in der Region verankert. TRUMPF und das FBH arbeiten bei brillanten Hochleistungs-Diodenlasern bereits seit einigen Jahren zusammen. So finanziert TRUMPF mehrere Doktorandenstellen am Institut. „Aus unseren Forschungstätigkeiten sind in den vergangen Jahren viele Patente entstanden, mit denen sich Hochleistungs-Diodenlaser weiter verbessern lassen", so FBH-Direktor Günther Tränkle. „Der Bedarf ist da und wird weiter wachsen, denn der weltweite Markt für Lasersysteme, die Metalle schneiden und bearbeiten können, ist gewaltig." Bei bestimmten Materialen – beispielsweise gehärtetem Stahl für die Sicherheitszelle im Automobil – ist der Laser als Werkzeug praktisch konkurrenzlos und aus der Fertigung nicht mehr wegzudenken.

In Sachen Leistungsdichte und Umwandlungsrate von Strom in Licht gehören die Diodenlaser von FBH und TRUMPF derzeit zu den leistungsfähigsten weltweit. In den Labors werden immer neue Rekorde erreicht. Die Berliner TRUMPF Niederlassung, die nicht nur in den Bereichen Halbleiter-Laserphysik, Aufbautechnik, Konstruktion und Simulation gut aufgestellt ist, sondern auch über einen eigenen Reinraum verfügt, soll die Entwicklung weiter beschleunigen.

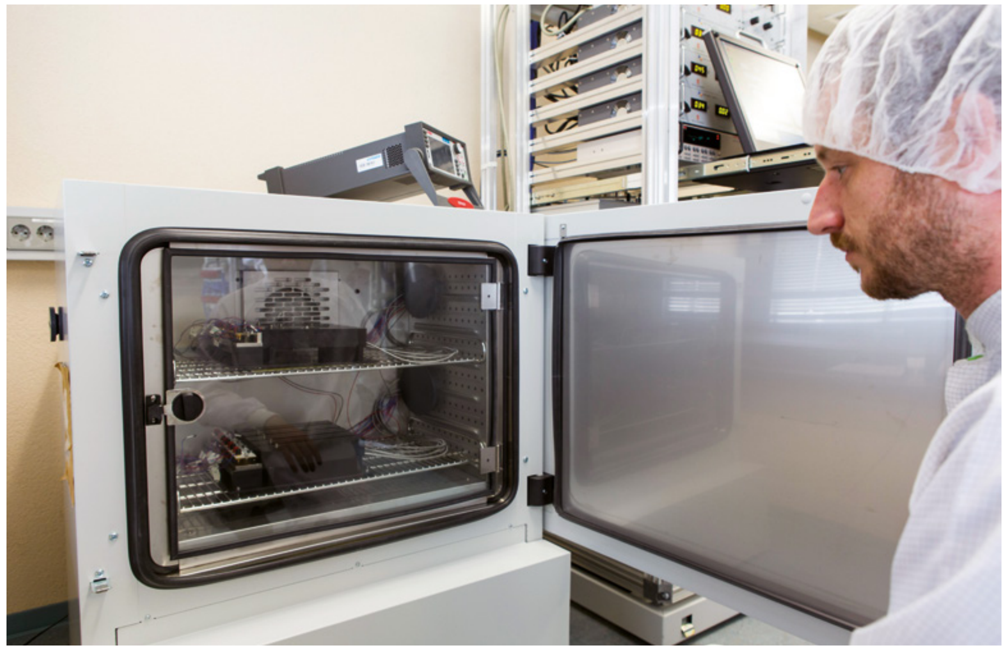
From strategy to implementation – the Zwanzig20 consortium *Advanced UV for Life*

ADVANCED **UV** FOR LIFE

In the first quarter of 2015, *Advanced UV for Life*, one of FBH's most extensive collaborations was very positively assessed by the advisory board and a committee of experts, commissioned by the Federal Ministry of Education and Research (BMBF). Strategy and structure of the consortium have been evaluated as qualified to push the scientific and economic development opportunities of UV LEDs. The consortium coordinated by FBH was therefore given thumbs up for the implementation phase. *Advanced UV for Life*'s overall aim is to promote the technological development, the availability, and the use of UV LEDs. The corresponding developments at FBH take a central role in the consortium. So far, the FBH is involved in over 40 % of the funded projects along the entire value chain of the consortium. *Advanced UV for Life* is financed by the BMBF as part of the program "Zwanzig20 – Partnerschaft für Innovation" (Twenty20 – Partnership for Innovation) and supported with up to 45 million € until 2019.

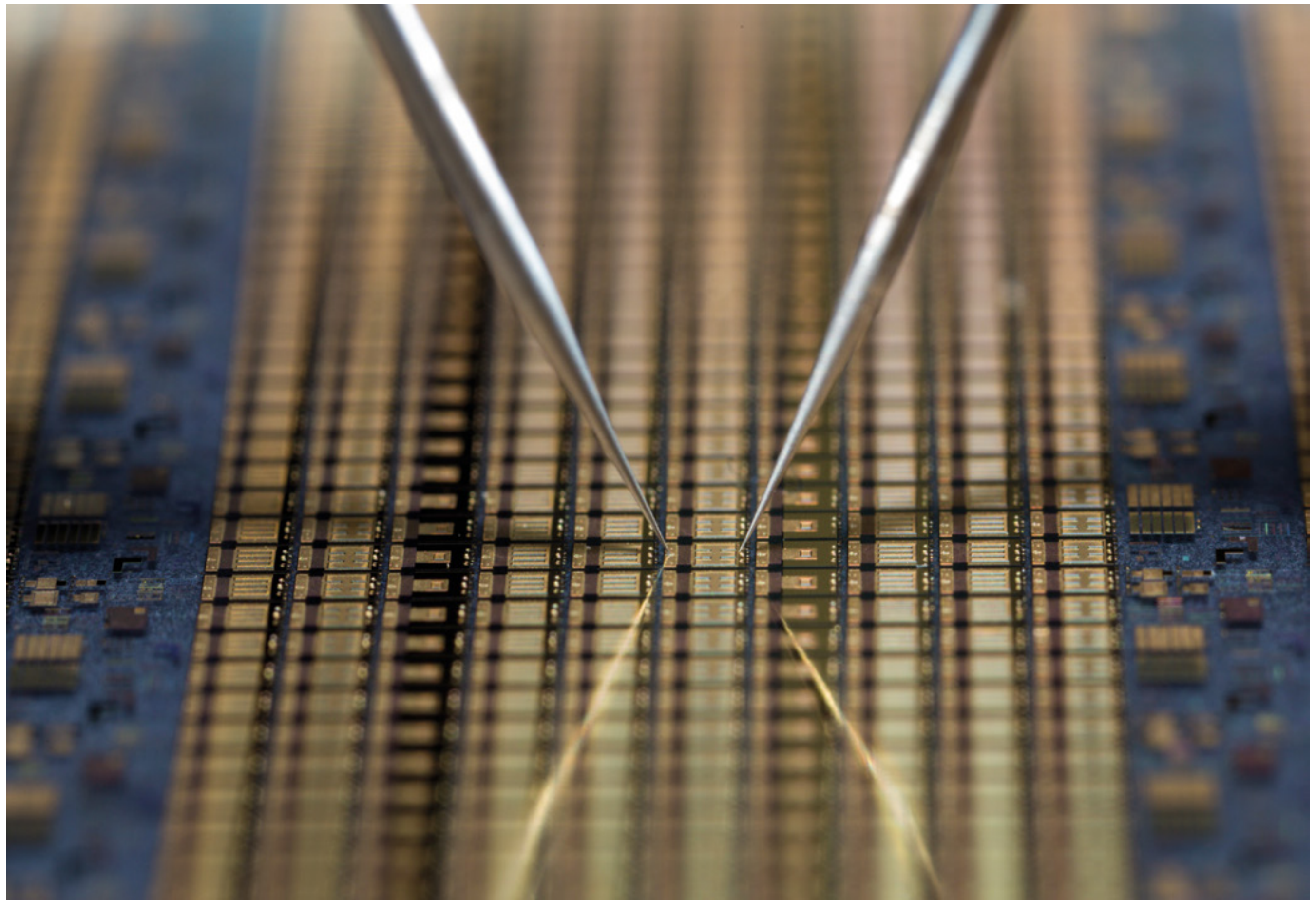
Currently, 35 industrial and academic partners from all over Germany join their forces, thus covering all essential competencies: from the material to UV LEDs and UV photodiodes to modules and systems with tailored properties to the final application. Applications include UV LED based components, systems, and processes. Meanwhile, a major prerequisite for the smooth development of UV LEDs is fulfilled by keeping an up-to-date process chain on hand. Accordingly, the main focus of the Joint Lab GaN Optoelectronics, which is jointly operated by FBH and TU Berlin and is actively involved in *Advanced UV for Life*, was on upgrading the technical equipment in 2015. Acquisitions comprise an epitaxy system installed at FBH, thus doubling the development capacity, and an atomic force microscope at TU Berlin for characterization of epitaxial wafers. Additionally, a mapper for the automated on-wafer characterization of UV LED properties as well as a laser scriber and a wafer breaker for wafer dicing were put into operation.

Now, the large number of projects in the seven strategic topics of *Advanced UV for Life* can be handled without capacity limitations. Besides four ongoing projects that are focused on UV LED development, 12 further projects ranging from basic technologies via UV LED based applications through to strategy and management were started in 2015. Three R&D projects within the consortium were successfully completed in 2015. Additionally, the advisory board supported 15 further projects that are expected to be started in 2016. Additional information on *Advanced UV for Life*'s network management activities is provided on page 44.



Aging measurement setup for UV LEDs.
Alterungsmessplatz für UV-Leuchtdioden.

Von der Strategie zur Umsetzung – das Zwanzig20-Konsortium *Advanced UV for Life*



On-wafer characterization of UV LEDs.
Charakterisierung von UV-Leuchtdioden auf dem Wafer.

Advanced UV for Life, eine der größten und umfassendsten Kooperationen des FBH, wurde vom Beirat des Konsortiums und einem vom Bundesministerium für Bildung und Forschung (BMBF) beauftragten Expertengremium im ersten Quartal 2015 sehr positiv evaluiert. Strategie und Struktur des Konsortiums wurden für geeignet befunden, um die wissenschaftlichen und wirtschaftlichen Entwicklungs- und Verwertungsmöglichkeiten von UV-Leuchtdioden (LEDs) voranzutreiben. Damit gab es grünes Licht für die Umsetzungsphase des vom FBH koordinierten Vorhabens, dessen Aktivitäten darauf zielen UV-LEDs technologisch so weiterzuentwickeln und verfügbar zu machen, dass sie in breitem Maße genutzt werden können. Die entsprechenden Entwicklungsarbeiten am FBH nehmen dabei eine zentrale Rolle innerhalb des Verbundes ein. Das FBH ist aktuell an mehr als 40 % der geförderten Projekte entlang der Wertschöpfungskette des Konsortiums beteiligt. *Advanced UV for Life* wird vom BMBF im Rahmen des Programmes „Zwanzig20 – Partnerschaft für Innovation" mit bis zu 45 Millionen € bis zum Jahr 2019 gefördert.

Derzeit bündeln 35 Partner aus Forschung und Industrie aus ganz Deutschland ihre Kräfte. Sie decken dabei alle notwendigen Kompetenzen ab: vom Material, UV-LEDs und -Fotodioden über Module und Systeme mit maßgeschneiderten Eigenschaften bis hin zu den Anwendungen, zu denen vielfältige UV-LED-basierte Komponenten, Systeme und Prozesse gehören. Inzwischen verfügt *Advanced UV for Life* über eine lückenlose Prozesskette auf dem neuesten technischen Stand und erfüllt damit eine der zentralen Voraussetzungen für die reibungslose Entwicklung von UV-Leuchtdioden. Entsprechend lag der Hauptfokus des Joint Lab GaN Optoelectronics, das FBH und TU Berlin gemeinsam betreiben und das aktiv in *Advanced UV for Life* eingebunden ist, im Jahr 2015 auf dem Ausbau der technischen Ausstattung. Neu angeschafft wurden etwa am FBH eine Epitaxieanlage, die die Fertigungskapazitäten verdoppelt, und ein Rasterkraftmikroskop zur Charakterisierung der epitaxierten Wafer an der TU Berlin. Auch ein Mapper zur automatisierten On-Wafer-Charakterisierung der LED-Eigenschaften sowie eine Anlage zum Ritzen und Brechen der UV-LED-Chips wurden in Betrieb genommen.

Mit dieser Ausstattung kann die große Anzahl von Projekten in den sieben strategischen Bereichen von *Advanced UV for Life* ohne Kapazitätsbegrenzungen durchgeführt werden. Zusätzlich zu vier bereits laufenden Projekten im Bereich der Entwicklung von UV-LEDs sind 12 weitere Projekte gestartet, deren Spektrum von grundlegenden Technologien über UV-LED-basierte Anwendungen bis hin zu Strategie und Management reichen. Drei F&E-Projekte des Konsortiums wurden 2015 erfolgreich abgeschlossen. Der Beirat hat zudem 15 weitere Projekte befürwortet, die voraussichtlich im Jahr 2016 starten werden. Weitere Informationen zum Management von *Advanced UV for Life* sind auf S. 45 zu finden.

Third funding period granted for Collaborative Research Centre 787

The Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) has granted the Collaborative Research Centre 787 *Semiconductor Nanophotonics: Materials, Models, Devices* another four-year funding period after being successfully assessed in summer by the DFG senate. The FBH continues to collaborate in sub-project C9: nitride-based laser diodes for the deep UV. Sub-project A7 was newly added, investigating the dynamic behavior of quantum dots and coupled quantum wells using pump probe spectroscopy.

SFB 787 has been funded since 2008 and combines three complementary areas of research aiming at the development of novel photonic and nanophotonic devices. The close collaboration between the different research areas and their mutual integration will help to explore new functionalities of nanophotonic devices and open new areas of applications. These include quantum communication systems that are based on q-bit and entangled photon emitters, quantum dot lasers and optical amplifiers for ultra-high bit rate Ethernet as well as UV laser diodes for water purification, UV curing, and medical diagnostics.

Dritte Förderperiode für Sonderforschungsbereich 787 bewilligt

Die Deutsche Forschungsgemeinschaft (DFG) hat für den Sonderforschungsbereich 787 *Halbleiter Nanophotonik: Materialien, Modelle, Bauelemente* ab 2016 eine weitere Förderung für vier Jahre bewilligt. Dies hat der Senat der DFG nach der positiven Begutachtung im Sommer entschieden. Das FBH ist weiterhin am Teilprojekt C9: Nitrid-basierte Laserdioden für das tiefe UV beteiligt. Neu hinzu kommt das Teilprojekt A7, in dem das dynamische Verhalten von Quantenpunkten und gekoppelten Quantengräben mit Pump-Probe-Spektroskopie untersucht wird.

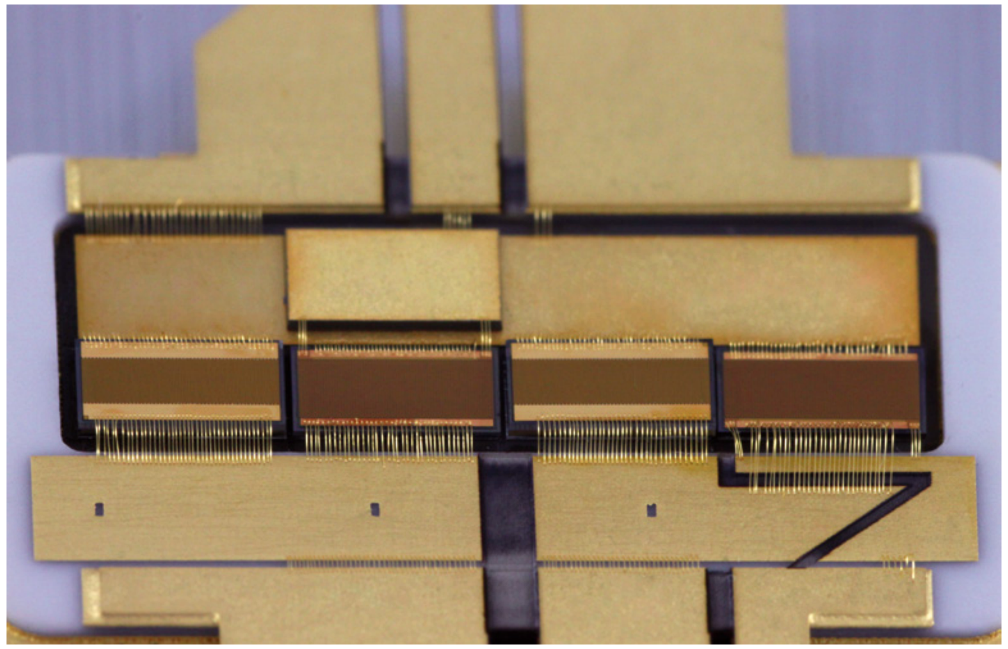
Der seit 2008 geförderte Sonderforschungsbereich vereint drei sich ergänzende Forschungsbereiche, die auf die Entwicklung neuartiger photonischer Bauelemente abzielen. Durch die enge Zusammenarbeit und Abstimmung sollen neue Funktionalitäten photonischer und nanophotonischer Bauelemente untersucht werden. Dies könnte neuartige Anwendungen erschließen, wie etwa Quantenkommunikations-Systeme, die auf Q-Bit- und verschränkten Photonenemittern basieren. Auch Quantenpunktlaser und optische Verstärker für ultrahochbitratiges Ethernet sowie UV-Laserdioden, die zur Wasserdesinfektion, UV-Härtung und medizinischen Diagnostik eingesetzt werden, gehören dazu.

Fast, efficient switching – thanks to *HiPoSwitch*

HiPoSwitch, an EU group-project coordinated by the FBH, has successfully developed lightning-fast, high-efficiency gallium nitride power switches. These are essential for producing energy-efficient, compact, and light-weight power converters that make electrical energy useable. Computers, smartphones, LEDs, and chargers for instance cannot use electrical energy in that form – the line voltage must be converted from AC to DC, for example. The reverse conversion (DC→AC) is also commonly used, such as in solar panel inverters. Anyway, the market potential is enormous, since these converters are found in nearly every electronic device.

The project, completed in 2015, bundled the know-how of eight European institutional and industrial project partners yielding normally-off gallium nitride (GaN) power transistors that were developed up to the prototype. Power converters using these novel GaN transistors have less than half the losses of existing technologies and make conversion efficiencies of over 98 % practical. GaN possesses ideal physical properties for a semiconductor. GaN components are therefore very efficient and very fast power switches. And this is because of their low on-state resistance with negligible losses. At the same time, higher switching frequencies mean that passive elements of the power converter, i.e. the inductive coils and capacitors, can be considerably smaller in size – a definite improvement on the systems side.

GaN has already been utilized in microwave transistors for a long while and applied in thin layers mostly on silicon carbide (SiC) substrates. This technology has been further developed by FBH over the last few years for 600 volt-rated power transistor switches. This works well, but it is too expensive for mass markets. As an alternative, the processes developed for SiC can be transferred to considerably more cost-effective, but technologically more challenging



GaN-based half bridge for power converters.
GaN-basierte Halbbrücke für Leistungskonverter.

silicon (Si) substrates. Among other accomplishments, FBH was so successful in optimizing the processing of GaN switching transistors on SiC and Si that nearly ideal components became feasible. They are optimized for switching 600 V, have an on-resistance of 75 mΩ and handle a maximum of 120 A.

Close cooperation with the project partners along the whole value chain was crucial for subsequent valorization, from epitaxy to the final system demonstrator. The companies EpiGaN and Aixtron, for example, were responsible for epitaxy on silicon, increasing the wafer diameter to 6" or even 8" at the same time – a necessary step towards cost-effective industrial production. Chip-manufacturer Infineon matched up the newly developed GaN technology with a Si process line for industrial production of power semiconductors. The Austrian company Artesyn is positioned at the end of the value-added chain as a systems-level partner. They developed

Normally-off switching transistor for power electronic applications.
Selbstsperrender Schalttransistor für die Leistungselektronik.

a 3 kW rectifier for telecommunications applications including cellular base stations. This unit converts line voltage to DC with an efficiency of 98 %. A specialized switching topology was developed and implemented that is matched to the properties of the GaN switching transistors.

Thanks to their broad usage, the market for energy-saving power converters is enormous. Efficient converters considerably contribute to saving primary energy, reducing volume and weight at the same time. This is what makes the novel GaN-based technology also attractive for aerospace applications.

Schnell und effizient schalten – dank *HiPoSwitch*

In dem vom FBH geleiteten EU-Verbundprojekt *HiPoSwitch* ist es gelungen, sehr effiziente und blitzschnelle Galliumnitrid-Leistungsschalter zu entwickeln. Sie sind die Basis für energiesparende, kompakte und leichte Leistungskonverter, die elektrische Energie nutzbar machen. Denn kaum ein elektrisches Gerät verträgt die normale Netzspannung. Computer, Smartphones, LED-Lampen oder Ladegeräte etwa können mit elektrischer Energie in dieser Form nichts anfangen – die Netzspannung muss beispielsweise von Wechsel- in Gleichstrom umgewandelt werden. Auch der umgekehrte Weg ist denkbar, etwa bei Invertern für Solarmodule. Das Marktpotenzial ist jedenfalls riesig, da solche Wandler in beinahe jedem Gerät sitzen.

Das 2015 abgeschlossene Projekt bündelte das Know-how von acht europäischen Partnern aus Forschung und Industrie, die selbstsperrende Galliumnitrid (GaN)-Leistungstransistoren bis zum Prototypen entwickelten. Energiekonverter, die diese neuartigen GaN-Transistoren nutzen, können die Verluste gegenüber existierenden Technologien halbieren. Sie ermöglichen eine Konversionseffizienz von 98% und mehr. Dank der optimalen physikalischen Parameter des Halbleitermaterials Galliumnitrid sind GaN-Bauteile sehr effiziente und sehr schnelle Leistungsschalter – aufgrund ihres niedrigeren Einschaltwiderstandes ohne signifikante Einschaltverluste. Eine höhere Schaltfrequenz bedeutet zugleich, dass die passiven Elemente der Energiekonverter, also Spulen und Kondensatoren, wesentlich kleiner dimensioniert werden können. Das ist eine deutliche Verbesserung auf der Systemseite.

GaN wird bereits seit Längerem für Mikrowellentransistoren verwendet und in hauchdünnen Schichten meist auf Siliziumcarbid (SiC)-Substraten aufgebracht. Eine Technologie, die am FBH in den letzten Jahren in Richtung von Leistungs-Schalttransistoren für den 600-Volt-Betrieb weiterentwickelt wurde. Das funktioniert gut, ist aber zu teuer für den Massenmarkt. Daher wurde die auf SiC entwickelte Technologie gemeinsam mit den Partnern auf deutlich kostengünstigere, aber technologisch anspruchsvollere Siliziumsubstrate (Si) übertragen. Dabei ist es gelungen nahezu ideal funktionierende GaN-Schalttransistoren auf SiC und Si zu prozessieren. Sie sind darauf optimiert, 600 Volt zu schalten, haben einen Einschaltwiderstand von 75 mΩ und liefern eine maximale Stromstärke von 120 Ampere. Wichtig für die spätere Verwertung war die Zusammenarbeit mit den Partnern entlang der Wertschöpfungskette, von der Epitaxie bis zum Systemdemonstrator. So waren im Projekt beispielsweise die Partner EpiGaN und Aixtron für die Epitaxie auf Silizium verantwortlich. Sie erweiterten das epitaktische Wachstumsverfahren zugleich auf Waferdurchmesser von bis zu 8 Zoll – ein notwendiger Schritt in Richtung einer kostengünstigen industriellen Fertigung. Der Chiphersteller Infineon etablierte die neu entwickelte GaN-Technologie auf einer Si-Prozesslinie für die industrielle Produktion von Leistungshalbleitern. Dem Systempartner Artesyn Austria ist es schließlich gelungen, einen 3-kW-Telecom-Rectifier für Mobilfunk-Basisstationen zu entwickeln. Dieser konvertiert die Netz-Wechselspannung in Gleichspannung mit einem Wirkungsgrad von 98 %. Dazu wurde eine spezielle, auf die Eigenschaften von GaN-Schalttransistoren angepasste Schaltungstopologie entwickelt und realisiert.

Dank ihrer hohen Verbreitung ist der Markt für energiesparende Leistungskonverter riesig. Mit effizienteren Umrichtern kann nennenswert Primärenergie eingespart werden und zusätzlich lassen sich Volumen und Gewicht reduzieren. Das macht die neue GaN-basierte Technologie auch für Anwendungen in der Luft- und Raumfahrt hoch attraktiv.

For immediate testing – industrial-suited, miniaturized diode lasers with fiber connection

More and more, customers and partners request modules and demonstrators from the FBH that they can easily integrate into their own systems for testing without performing major adjustments. The Ferdinand-Braun-Institut is taking these requirements increasingly into account during its research activities. *FaBriDi*, a joint project terminated in 2015, yielded fiber-coupled demonstrators for industrial use that were developed by FBH's Laser Modules Lab in cooperation with regional companies from Berlin-Adlershof. Diode laser chips with highly brilliant laser radiation were integrated into industry-compatible, standardized Butterfly housings. With the implemented fiber connector, the developed laser sources can be easily integrated and applied in various systems.

The laser modules comparable in size to matchboxes deliver up to 3 watt optical output power from a single-mode fiber at a coupling efficiency of almost 50 %. A low-mode number fiber with bigger core diameter yields almost 5 watt output power with a coupling efficiency near 60 %. With these results, the FBH modules outperform currently available commercial diode laser sources by five to ten times regarding radiance and brilliance. These world-wide unique results were demonstrated at 1064 nm, but can be transferred to other wavelengths.

Fiber-coupled highly brilliant diode lasers suited for pumping of solid-state and fiber lasers as well as for frequency conversion. Fasergekoppelte hochbrillante Diodenlaser zum Pumpen von Festkörper- und Faserlasern oder zur Frequenzkonversion.

Direkt testen – industrietaugliche, miniaturisierte Diodenlaser-Module mit Faseranschluss

Immer mehr Kunden und Partner möchten die Module und Demonstratoren aus dem FBH einfach in ihre eigenen Systeme integrieren, um sie ohne größere Anpassungen zu testen. Diese Anforderungen berücksichtigt das Ferdinand-Braun-Institut zunehmend bei seinen Entwicklungen. So bietet das FBH in dem 2015 abgeschlossenen Verbundprojekt *FaBriDi* fasergekoppelte Demonstratoren für den Industrieeinsatz, die das Laser Modules Lab gemeinsam mit Adlershofer Unternehmen entwickelte. Diodenlaserchips mit hochbrillanter Laserstrahlung wurden dazu in industriekompatible, standardisierte Butterfly-Gehäuse integriert. Durch den vorhandenen optischen Faseranschluss können die Laserstrahlquellen unkompliziert in verschiedene Systeme integriert und angewandt werden.

Die Lasermodule, deren Größe vergleichbar mit einer Streichholzschachtel ist, liefern bis zu 3 Watt optische Leistung aus einer Single-Mode-Faser bei einer Koppeleffizienz von knapp 50 %. Aus einer Low-Mode-Number-Faser mit größerem Kerndurchmesser kommen fast 5 Watt Ausgangsleistung bei einer Koppeleffizienz von knapp 60 %. Damit übertreffen sie die bisher kommerziell verfügbaren Diodenlaser-Strahlquellen um das 5- bis 10-fache in puncto Strahldichte und Brillanz. Diese weltweit einzigartigen Ergebnisse wurden bei 1064 nm demonstriert und sind auf andere Wellenlängen übertragbar.

Miniaturized optode with two-wavelength diode lasers successfully passes field test

In the frame of the *DiLaRa* project, a compact optode with implemented two-wavelength diode laser has been developed. The novel diode lasers from FBH's Laser Sensors Lab emit light from only one chip alternatingly on two different wavelengths, which are determined by separately controllable sections of the laser and by gratings implemented into the semiconductor chip. The monolithic light sources – sized as small as rice grains on chip-level – enabled FBH to realize a compact detector head. This optode has the dimensions of a laser pointer and is capable of performing SERDS measurements. With the Shifted Excitation Raman Difference Spectroscopy (SERDS) method, Raman signals can be separated efficiently from disturbing background signals such as fluorescence or ambient light. This characteristic for the first time allows for undisturbed Raman measurements, delivering usable results even outside the lab. The resulting "fingerprint" spectra render important information on the chemical composition of the sample examined.

The miniaturized optode has been successfully utilized together with a portable measurement environment in a field test during completion of the EU project *USER-PA*. In cooperation with the Prototype Engineering Lab, a programmable laser control, a battery-based power supply, and a compact spectrometer were integrated into a robust case. This portable system allowed for the first time ever for field measurements – in this case in agriculture – using the SERDS method. With it, in situ Raman examinations of apples and leaves under daylight conditions were successfully demonstrated (see also p. 72). Within the European network *USER-PA*, international Partner from different research disciplines joined forces to create a sustainable technological platform for precision agriculture. The name stands for Usability of Environmentally sound and Reliable techniques in Precision Agriculture.

The subsequently started *I4S* (Intelligence for Soil) project, which is part of the center for soil research *BonaRes* (soil as sustainable resource for bio-economy), is dealing with intelligent technical solutions for sustainable agriculture. Like already before in *USER-PA*, FBH closely cooperates in this subproject with the Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB). Building up on the jointly gained findings, the scientific foundations for a sustainable soil use shall be developed in *I4S*. The project aims at establishing a sensor-based system that especially delivers recommendations for a site-specific fertilization management, thus improving soil function and reducing environmental stress. Mobile soil sensors yet to be

Highlights Schlaglichter

developed and matching soil process models are expected to deliver special high-resolution information that is easy-to-handle by farmers. With this system, for nearly every square meter soil a cost-efficient method shall be at hand allowing to control fertilization of nutrients like nitrogen, phosphor, and potassium according to the actual needs. FBH will develop a mobile Raman measurement system for in situ soil analysis that is based on the SERDS method – as one of the components for the sensor-based overall system.

Miniaturisierte Optode mit Zwei-Wellenlängen-Diodenlaser erfolgreich im Praxistest

In situ Raman field test using FBH's portable SERDS measurement system to examine apples and leaves.
Vor-Ort-Raman-Feldmessung an Äpfeln und Blättern mit dem portablen SERDS-Messsystem aus dem FBH.

Im Rahmen des Projektes *DiLaRa* wurde eine kompakte Optode mit implementiertem Zwei-Wellenlängen-Diodenlaser entwickelt. Der im Laser Sensors Lab des FBH entwickelte neuartige Diodenlaser emittiert auf nur einem Chip alternierend Licht auf zwei verschiedenen Wellenlängen. Diese sind über separat ansteuerbare Sektionen im Laser und in den Halbleiterchip implementierte Gitter festgelegt. Die auf Chipebene reiskorngroßen, monolithischen Lichtquellen ermöglichten es, einen SERDS-tauglichen, kompakten Messkopf in der Größe eines Laserpointers zu realisieren. Mit der Shifted Excitation Raman Difference Spectroscopy (SERDS) Messmethode lassen sich Raman-Signale effizient von Störsignalen wie Fluoreszenz oder Umgebungslicht trennen. Dies erlaubt es erstmalig störungsfreie Raman-Messungen durchzuführen, die auch außerhalb des Labors verwertbare Ergebnisse liefern. Die damit sichtbaren „Fingerprint"-Spektren liefern wichtige Informationen über die chemische Zusammensetzung der untersuchten Probe.

Die miniaturisierte Optode wurde zusammen mit einer portablen Messumgebung erfolgreich in einem Feldexperiment zum Abschluss des EU-Projektes *USER-PA* eingesetzt. In Zusammenarbeit mit dem EntwicklungsZentrum wurden die programmierbare Laseransteuerung, die Akku-basierte Stromversorgung und ein kompaktes Spektrometer in einen robusten Koffer integriert. Dieses portable System erlaubte zum ersten Mal Feldmessungen mit der SERDS-Methode – wie hier in der Landwirtschaft. Damit wurde die Vor-Ort-Raman-Untersuchung von Äpfeln und Blättern unter Tageslichtbedingungen erfolgreich demonstriert (siehe auch S. 72). Im europäischen Netzwerk *USER-PA* hatten sich internationale Partner aus verschiedenen Forschungsdisziplinen zusammengetan, um eine zukunftsfähige und nachhaltige technologische Plattform für den Präzisionsgartenbau zu schaffen. Der Name steht für USability of Environmentally sound and Reliable techniques in Precision Agriculture.

Auch das im Anschluss gestartete Projekt *I4S* (Intelligence for Soil – Integriertes System zum ortsspezifischen Management der Bodenfruchtbarkeit) im Rahmen des Zentrums für Bodenforschung *BonaRes* (Boden als nachhaltige Ressource für die Bioökonomie) beschäftigt sich mit intelligenten technischen Lösungen für eine nachhaltige Landwirtschaft. Wie bereits in *USER-PA* kooperiert das FBH in diesem Teilprojekt erneut eng mit dem Leibniz-Institut für Agrartechnik Potsdam-Bornim (ATB). Auf den gemeinsam gewonnenen Erkenntnissen aufbauend, sollen in *I4S* nun die wissenschaftlichen Grundlagen für eine nachhaltige Bodennutzung erarbeitet werden. *I4S* zielt auf die Entwicklung eines sensorgestützten Systems, das insbesondere Empfehlungen für ein ortsspezifisches Düngungsmanagement geben soll. Damit sollen sich Bodenfunktionen verbessern und Umweltbelastungen vermindern lassen. Neu zu entwickelnde mobile Bodensensoren und darauf abgestimmte Bodenprozessmodelle

sollen räumlich hoch aufgelöste Informationen liefern, die für Landwirte einfach handhabbar sind. Für nahezu jeden Quadratmeter Boden soll dann eine kostengünstige Methode zur Verfügung stehen, anhand derer die Düngung mit Nährstoffen wie Stickstoff, Phosphor und Kalium bedarfsgerecht gesteuert werden kann. Das FBH wird als einen Bestandteil des sensorgestützten Gesamtsystems ein mobiles Raman-Messsystem für die Vor-Ort-Bodenanalyse entwickeln, das auf der SERDS-Methode basiert.

Looking behind the scenes of research and development – the technical preconditions for state-of the art devices

High-tech semiconductor devices offer specialized functionalities, each tailor-made for the specific application. Core part are chips the size of rice grains, consisting of tiny, only a few micrometer or even nanometer small structures. In order to make the complex devices work frictionless, they are manufactured in (almost) dust-free cleanrooms. The air permanently circulates in these special labs using sophisticated filter systems implemented in both ceiling and floor, thus cleaning the air from possible particles. Additionally, specially designed cleanroom clothing, head covers, face masks, and gloves used by the scientific and technical staff ensure that no or as few as possible skin scales, hair, and dust get from the outside into the cleanroom. The reason for such elaborate measures is that most of these contaminations are distinctly bigger than the delicate structures of the devices and can therefore destroy them.

FBH currently operates around 1,600 square meter laboratory and 750 square meter cleanroom area of the ISO classes 5 and 6. This means that in one cubic meter air only a maximum amount of various determined particle sizes is permitted. For cleanroom class ISO 5, for example, no more than 3,520 particles greater or equal 0.5 micrometers (µm) are allowed. To satisfy the requirements of this cleanroom class, 98 - 99 % of all particles > 0.5 µm are filtered from the ambient air – measurements of the institute's surrounding air have yielded an average of 246,069 particles > 0.5 µm per cubic meter air. For comparison, the diameter of a human scalp hair is around 50 µm.

Ventilation system ensuring stable temperature conditions as well as a constant humidity in the laboratories.
Lüftungsanlage, die für gleichmäßige Temperaturen und Luftfeuchtigkeit in den Laboren sorgt.

Safeguarding smooth cleanroom operation – the Technical Services

Cleanroom operation and maintenance of the equipment and technical infrastructure required to develop and process semiconductor devices is complex. Thus, the institute employs the 11-headed Technical Services team whose work lays the foundations for state-of-the-art devices from the FBH – from cleanroom technology and domestic engineering to the institute's workshop. Tasks of the Technical Services are not restricted to laboratory operation, but also involve all technical supply and disposal facilities at the institute including installations and equipment for basic supply, surveillance, and maintenance. The team plans and develops technically complex solutions including investment and repair measures. It advises in all matters related to lab technology and suggests solution approaches for its use in science. Most recently, this expertise was in demand during planning and realization of FBH's extension building, which has been put into operation at the end of 2015, offering 1,800 square meter laboratory and office space. Before, in 2009, the air conditioning and cleanroom technology was updated with funds from Germany's Konjunkturpaket II (economic stimulus package), resulting in more operational safety and less downtime. Due to an improved energy management and optimization of maximum loads, operational costs additionally decreased.

Cold water distribution regulating the temperature in the laboratories.
Kaltwasserverteilung zum Temperieren der Labore.

Six out of eleven colleagues are taking care of the technical equipment and processes. One person is responsible for cleanroom services, therefore providing the protective clothing necessary for thorough cleanroom operation including cleanroom suits, head covers, and gloves. An in-house construction worker and three further colleagues in the workshop complete the team.

Laboratory and cleanroom operation comprises the following areas:

- ***Power supply:*** Three transformers each delivering 630 kVA distribute their power via five main building distribution boards and several sub-distribution units to the respective consumption point. To ensure operation of vital and security-relevant equipment, a diesel generator set along with an uninterrupted power supply (UPS) is kept available.

- ***Refrigeration:*** Four cooling generators with a refrigerating capacity of 1600 kW cool down as well as dehumidify the air and ensure cooling of processes.

- ***Gas supply:*** Two central gas supply systems safeguard the requirements of FBH's process laboratories in respect of special gases. Nitrogen and hydrogen are additionally provided via big storage tanks administered by a control and monitoring system.

- ***Ultra-pure and chemical waste water:*** Municipal water is treated in several steps to obtain ultra-pure water. Before discharging into the public waste water system, used water is neutralized and cleansed from potential impurities that may be caused by technological processes.

- ***Vacuum and compressed air:*** Basic supply for all chemical and physical labs is provided through six vacuum pumps and two screw compressors.

- ***Air conditioning:*** Five main air conditioning and several ventilation systems ensure clean air, stable temperature conditions, and a constant humidity in the cleanroom and the laboratories.

An important building block within research activities – FBH's workshop
An in-house precision mechanics workshop with CNC and conventional machine tools is also integral part of the Technical Services. Three staff members manufacture and design individual workpieces, apparatuses, measurement and mounting setups. Furthermore, expensive or no longer available spare parts for cleanroom equipment as well as for research operation are crafted. This support is indispensable for FBH's scientists since many of the developments are realized for the first time ever and therefore require specialized, tailored parts and apparatuses. Thus, the first prototypes are often manufactured in this workshop. The workshop team provides comprehensive support during the whole development process, from the first idea to CAD drawings and 3D models to the selection of materials. It additionally counsels when it comes to the optimum construction form, suggests possible optimizations and thus helps to ensure device functionality.

CNC lathe machine in the FBH workshop.
CNC-Drehmaschine in der FBH-Werkstatt.

Blick hinter die Kulissen von Forschung und Entwicklung – die technischen Voraussetzungen für State-of-the-Art-Bauelemente

High-Tech-Halbleiterbauelemente bieten spezialisierte, auf die jeweilige Anwendung zugeschnittene Funktionalitäten. Ihr Herzstück sind reiskorngroße Chips, die aus winzigen, nur wenige Mikrometer oder Nanometer kleinen Strukturen bestehen. Damit die komplexen Bauelemente reibungslos funktionieren, werden sie in (fast) staubfreien Reinräumen hergestellt. In diesen Speziallaboren wird die Luft mit aufwändigen Filtersystemen in Decke und Boden permanent umgewälzt und so von möglichen Partikeln gereinigt. Zusätzlich sorgen Spezialanzüge, Kopfhauben, Mundschutz und Handschuhe der wissenschaftlichen und technischen Mitarbeiterinnen und Mitarbeiter dafür, dass keine oder so wenig Hautschuppen, Haare und Staub wie möglich von außen in den Reinraum gelangen. Die meisten dieser Verunreinigungen sind nämlich deutlich größer als die filigranen Strukturen der Bauelemente und können sie daher zerstören.

Rund 1.600 Quadratmeter Labor- und 750 Quadratmeter Reinraumfläche der ISO-Klassen 5 und 6 betreibt das FBH derzeit. Das bedeutet, dass sich in einem Kubikmeter Luft nur eine maximale Anzahl verschiedener festgelegter Partikelgrößen befinden dürfen. Bei Reinraum-Klasse ISO 5 sind das beispielsweise höchstens 3.520 Partikel größer oder gleich 0,5 Mikrometer (µm). Für diese Reinraum-Klasse werden am FBH daher 98 - 99 % aller

Highlights Schlaglichter

The laboratories are being supplied with hydrogen (50,000 l) and nitrogen (nearly 32,600 l) from big tanks.
Die Labore werden aus großen Tanks mit Wasserstoff (50.000 l) und Stickstoff (knapp 32.600 l) versorgt.

Partikel > 0,5 µm aus der Umgebungsluft herausgefiltert. Messungen der Außenluft hatten durchschnittlich 246.069 Partikel > 0,5 µm pro Kubikmeter Luft ergeben. Zum Vergleich, der Durchmesser eines menschlichen Kopfhaares liegt bei etwa 50 µm.

Den reibungslosen Reinraumbetrieb sichern – die Technischen Dienste
Der Reinraumbetrieb und die Wartung der für Halbleiterbauelemente erforderlichen Anlagen und Infrastruktur ist entsprechend aufwändig. Daher beschäftigt das FBH das 11-köpfige Team der Technischen Dienste, die mit ihrer Arbeit die Voraussetzungen für State-of-the-Art-Bauelemente aus dem FBH schaffen: von der Reinraum- und Haustechnik bis hin zur institutseigenen Werkstatt. Die Aufgaben der Technischen Dienste beschränken sich nicht auf den Betrieb der Labore, sondern umfassen sämtliche technische Ver- und Entsorgungseinrichtungen im Institut einschließlich aller Anlagen und Geräte zur Grundversorgung, Überwachung und Wartung. Das Team plant und erarbeitet technisch komplexe Lösungen inklusive Investitions- und Reparaturmaßnahmen. Es berät zudem in Fragen der Labortechnik und erstellt Lösungsansätze für deren Einsatz in der Wissenschaft. Zuletzt war diese Expertise gefragt, als es um die Planung und Realisierung des Ende 2015 bezogenen Erweiterungsbaus des FBH mit 1.800 Quadratmetern Labor- und Bürofläche ging. Zuvor wurde im Jahr 2009 die Klima- und Reinraumtechnik im Rahmen des Konjunkturpaketes II auf den neusten Stand gebracht. Dies hat zu mehr Betriebssicherheit und weniger Ausfallzeiten geführt. Durch ein verbessertes Energiemanagement und die Optimierung bei Höchstlasten sanken zudem mittelfristig die Betriebskosten.

Sechs der elf Kolleginnen und Kollegen kümmern sich um die technischen Anlagen und Prozesse, ein weiterer ist für den Reinraumservice verantwortlich. Das heißt, er stellt insbesondere die für den Reinraum nötige Schutzkleidung wie Reinraumanzüge, Hauben und Handschuhe bereit. Ein Haushandwerker und drei weitere Kollegen in der Werkstatt vervollständigen das Team.

Der Labor- und Reinraumbetrieb umfasst die folgenden Bereiche:

- ***Stromversorgung:*** Drei Transformatoren mit je 630 kVA verteilen ihre Leistung über fünf Gebäudehauptverteilungen und mehrere Unterverteilungen an die entsprechenden Abnahmestellen. Zur Sicherung des Betriebes von lebensnotwendigen und sicherheitsrelevanten Anlagen stehen ein Dieselaggregat sowie eine unterbrechungsfreie Stromversorgung (USV) zur Verfügung.

- ***Kälteerzeugung:*** Vier Kälteerzeuger mit einer installierten Kälteleistung von 1600 kW kühlen und entfeuchten die Luft und sorgen für die Kühlung von Prozessen.

- ***Gasversorgung:*** Zwei zentrale Gasversorgungssysteme sichern den Bedarf der Prozesslabore an Spezialgasen. Stick- und Wasserstoff werden zusätzlich aus großen Vorratstanks bereitgestellt und mithilfe eines Steuerungs- und Überwachungssystems verwaltet.

- ***Reinst- und Chemieabwasser:*** Für die Prozesse in den Laboren wird Stadtwasser in mehreren Stufen zu Reinstwasser aufbereitet. Vor der Einleitung in das öffentliche Abwassernetz wird es neutralisiert und von eventuellen Belastungen durch technologische Prozesse befreit.

- ***Vakuum und Druckluft:*** Die Grundversorgung wird zentral über sechs Vakuumpumpen und zwei Schraubenkompressoren für alle chemischen und physikalischen Labore bereitgestellt.

- ***Klimatisierung:*** Fünf Hauptklimaanlagen und mehrere Umluftanlagen sorgen im Reinraum und in den Laboren für reine Luft, stabile Temperaturverhältnisse und eine konstante Luftfeuchtigkeit.

Ein wichtiger Baustein im Forschungsbetrieb – die FBH-Werkstatt
Zu den Technischen Diensten gehört auch eine eigene feinmechanische Werkstatt mit CNC- und konventionellen Werkzeugmaschinen. Drei Mitarbeiter fertigen und entwerfen individuelle Werkstücke, Vorrichtungen, Mess- und Montage-Aufbauten. Hinzu kommen teure oder nicht mehr verfügbare Ersatzteile für Anlagen im Reinraum sowie für den Forschungsbetrieb. Für die Wissenschaftlerinnen und Wissenschaftler am FBH ist diese Unterstützung unverzichtbar, da viele Entwicklungen erstmalig realisiert werden und dafür spezialisierte Teile und Vorrichtungen maßgeschneidert werden müssen. Daher werden die ersten Prototypen oft in dieser Werkstatt gefertigt. Das Werkstatt-Team unterstützt dabei umfassend: von der ersten Idee über CAD-Zeichnungen und 3D-Modelle bis hin zur Materialauswahl. Es berät zudem bei der optimalen Bauform, schlägt mögliche Optimierungen vor und sichert so die Funktionsfähigkeit.

Colleagues during CNC milling in the workshop.
Kollegen beim CNC-Fräsen in der Werkstatt.

Matching the institute's size – FBH re-organizes its research activities

The Ferdinand-Braun-Institut has grown significantly in recent years. Whereas the institute employed 150 co-workers in 2005, the staff increased to almost 300 persons in 2015 – and thus nearly doubled in only ten years. In the light of this dynamic growth, organizational structures were refined and responsibilities shared across more shoulders in mid-2015.

FBH now organizes its R&D activities within labs and departments in three research areas: photonics, III-V electronics, and III-V technology. While the labs are dealing with the specific device developments, from basic research to the specific application, the departments provide the technical and scientific resources of the institute and develop them further. With its Prototype Engineering Lab, the FBH has created an additional active interface between industry and science in order to transfer excellent research results even more rapidly into market-oriented products, processes, and services. In every research area, the FBH closely cooperates with various universities, structurally in the frame of joint labs and with comprehensive university teaching in terms of content.

Passend zur Institutsgröße – FBH organisiert seine Forschung neu

In den vergangenen Jahren ist das Ferdinand-Braun-Institut deutlich gewachsen. So beschäftigte das FBH im Jahr 2005 noch 150 Mitarbeiterinnen und Mitarbeiter, 2015 arbeiteten fast 300 Personen am Institut – damit hat sich die Zahl der Beschäftigten in nur zehn Jahren beinahe verdoppelt. Vor diesem Hintergrund wurde ab Mitte 2015 die organisatorische Struktur weiterentwickelt und die Verantwortung im Institut auf mehr Schultern verteilt.

Seither organisiert das FBH seine F&E-Aktivitäten in drei Forschungsbereichen: Photonik, III/V-Elektronik und III/V-Technologie. Diese gliedern sich in Labs und Departments, wobei sich die Labs mit spezifischen Bauelemententwicklungen beschäftigen – von der Grundlagenforschung bis hin zur konkreten Applikation. Die Departments hingegen halten die technischen und wissenschaftlichen Ressourcen des Instituts bereit und entwickeln diese weiter. Mit dem Prototype Engineering Lab (EntwicklungsZentrum) hat das FBH zugleich eine aktive Schnittstelle zwischen Wirtschaft und Wissenschaft geschaffen, mit der exzellente Forschungsergebnisse noch schneller in marktorientierte Produkte, Verfahren und Dienstleistungen überführt werden können. In allen Forschungsbereichen kooperiert das FBH eng mit verschiedenen Universitäten: strukturell im Rahmen von Joint Labs und inhaltlich durch umfangreiche Lehrtätigkeiten.

Personnel & Awards
Personalia & Auszeichnungen

Ina Ostermay receiving the Total E-Quality certificate in Hamburg.
Ina Ostermay nimmt das Total E-Quality Prädikat in Hamburg entgegen.

Equal opportunity at FBH – Total E-Quality certificate and new contact person

In 2015, the FBH has been awarded for the third time with the Total E-Quality certificate, which is now valid for another three-year period. The award documents the exemplary and sustainably successful efforts regarding a balanced work and family life. The FBH was already honored in 2009 and 2012.

Just before, new equal opportunity officers were elected according to the schedule. Dr. Ute Zeimer, who had been in charge in all matters of equal opportunity and family friendliness at FBH since 2005 and who had also been the speaker of all equal opportunity officers of Forschungsverbund Berlin, was no longer available as candidate for re-election. Dr. Ina Ostermay was elected as new contact person, and Jacqueline Hopp was confirmed as substitution. Consequently, Ina Ostermay – as her first official act so to say – received the Total E-Quality certificate on behalf of the FBH.

Ina Ostermay is mother of a two-year old son and has been a scientific co-worker at FBH since 2011. As of 2013, she is responsible for the scientific aspects of all coating technologies provided by the institute's process technology. After her PhD thesis, completed in March 2010 at TU Dresden, she had been working for a high-tech company in Dresden.

Jacqueline Hopp is FBH's deputy equal opportunity officer since 2007. The mother of three children aged between seven and 18 years has been with the FBH for almost 25 years. As technical employee in the field of laser measurement technology she is responsible for characterization of low-power lasers.

Gleichstellung am FBH – Total E-Quality Prädikat und neue Ansprechpartnerin

Bereits zum dritten Mal hat das FBH das Total E-Quality Prädikat im Jahr 2015 für seinen Einsatz für Chancengleichheit erhalten; es gilt nun für weitere drei Jahre. Die Auszeichnung dokumentiert die vorbildliche Gleichstellungspolitik des Instituts und würdigt das nachhaltig erfolgreiche Engagement rund um die Vereinbarkeit von Familie und Beruf. Zuvor war das FBH bereits 2009 und 2012 ausgezeichnet worden.

Kurz zuvor wurden am FBH die Gleichstellungsbeauftragten turnusgemäß neu gewählt. Dr. Ute Zeimer, die sich seit 2005 um die Belange von Gleichstellung und Familienfreundlichkeit am FBH gekümmert hatte und auch die Sprecherin aller Gleichstellungsbeauftragten beim Forschungsverbund Berlin war, hatte sich nicht erneut zur Wahl gestellt. Neu gewählt wurde Dr. Ina Ostermay, als Stellvertreterin wurde Jacqueline Hopp bestätigt. Damit nahm Ina Ostermay, sozusagen als erste Amtshandlung, auch das Total E-Quality Prädikat für das FBH entgegen.

Ina Ostermay ist Mutter eines 2-jährigen Sohnes und seit 2011 am FBH als wissenschaftliche Mitarbeiterin beschäftigt, seit 2013 auch als wissenschaftlich Verantwortliche für alle Beschichtungstechnologien in der Prozesstechnologie. Im Anschluss an ihre Promotion im März 2010 an der TU Dresden war sie bei einem Dresdner High-Tech-Unternehmen beschäftigt.

Jacqueline Hopp ist seit 2007 als stellvertretende Gleichstellungsbeauftragte am FBH aktiv. Die Mutter von drei Kindern im Alter zwischen sieben und 18 Jahren ist seit fast 25 Jahren am Institut als technische Mitarbeiterin in der Laser-Messtechnik beschäftigt. Dort ist sie für die Charakterisierung von Low-Power-Lasern zuständig.

Best Oral Paper Award
At the "Electrical Performance of Electronic Packages and Systems" conference, the FBH talk "Process Robustness and Reproducibility of sub-mm Wave Flip-Chip Interconnect Assembly" presented by Sirinpa Monayakul, Siddhartha Sinha, Franz-Josef Schmückle, Michael Hrobak, Dimitri Stoppel, Olaf Krüger, Bernd Janke, and Nils Weimann was honored with the Best Oral Paper Award.

Best Oral Paper Award
Auf der Konferenz „Electrical Performance of Electronic Packages and Systems" wurde der FBH-Vortrag „Process Robustness and Reproducibility of sub-mm Wave Flip-Chip Interconnect Assembly" von Sirinpa Monayakul, Siddhartha Sinha, Franz-Josef Schmückle, Michael Hrobak, Dimitri Stoppel, Olaf Krüger, Bernd Janke und Nils Weimann mit dem Best Oral Paper Award ausgezeichnet.

First place in "Most Downloaded Journal of Crystal Growth Articles"
In June 2015, a joint publication of FBH, Hochschule Ruhr West, and Laytec was the most downloaded publication of the last 90 days. The paper describes in situ photoluminescence investigations during growth of InGaN LED structures in a MOVPE reactor.

Platz 1 bei „Most Downloaded Journal of Crystal Growth Articles"
Die gemeinsame Publikation von FBH, Hochschule Ruhr West und Laytec war im Juni 2015 die am meisten heruntergeladene Publikation aus dem Journal of Crystal Growth der letzten 90 Tage. Das Paper beschreibt in-situ Fotolumineszenzuntersuchungen beim Wachstum von InGaN-LED-Strukturen in einem MOVPE-Reaktor.

Wolfgang Heinrich

Wolfgang Heinrich re-elected as President of the European Microwave Association
At the turn of the year, FBH's long-term Microwave Department Head and Professor at Technische Universität Berlin Prof. Dr.-Ing. Wolfgang Heinrich took over the presidency of the European Microwave Association (EuMA) for another three-year term. He is already holding this function since 2010.

EuMA has members from all over Europe and adjacent nations. It is one of the internationally most important associations for scientists and engineers within the microwave field. The non-profit organization which is based in Belgium both encourages cooperation within the technology field and promotes microwave activities in Europe by means of education and training. It holds the annual European Microwave Week which comprises three conferences and an exhibition – apart from the International Microwave Week in the United States, this event is the most important microwaves conference world-wide with about 1,500 conference participants and typically 4,000 visitors.

Wolfgang Heinrich als Präsident der European Microwave Association wiedergewählt
Der langjährige Leiter des Departments Mikrowellentechnik des Ferdinand-Braun-Instituts und Professor an der Technischen Universität Berlin, Prof. Dr.-Ing. Wolfgang Heinrich, übernahm zum Jahreswechsel 2015 für weitere drei Jahre die Präsidentschaft der European Microwave Association (EuMA). Er nimmt dieses Amt bereits seit 2010 wahr.

Die EuMA hat Mitglieder in ganz Europa und den umliegenden Staaten und gilt als einer der international wichtigsten Zusammenschlüsse von Wissenschaftlern und Ingenieuren in der Mikrowellentechnik. Die gemeinnützige Organisation mit Sitz in Belgien fördert die Zusammenarbeit innerhalb des Fachgebiets und stärkt die Mikrowellen-Aktivitäten in Europa durch Aus- und Weiterbildung. Sie veranstaltet jährlich die European Microwave Week, die drei Konferenzen sowie eine Ausstellung umfasst – mit 1.500 Konferenzteilnehmern und typisch 4.000 Besuchern neben der International Microwave Week in den USA die weltweit wichtigste Mikrowellen-Konferenz.

Günther Tränkle

Günther Tränkle once again elected chairman of OpTecBB
At the end of October, a new board was chosen at the members' meeting of the Competence Network for Optical Technologies Berlin-Brandenburg OpTecBB. Already for the fourth time, FBH's Director Prof. Dr. Günther Tränkle has been elected as chairman. New members of the board are Peter Krause (deputy chairman), Martin Schell, Adrian Mahlkow, and Gerrit Rössler. OptecBB is an initiative of companies and scientific institutions in Berlin and Brandenburg aiming to jointly open up and exploit optical and microsystems technologies. The association, founded in 2002, has around 100 institutional members.

Günther Tränkle erneut zum OpTecBB-Vorsitzenden gewählt
Auf der Mitgliederversammlung des Kompetenznetzes Optische Technologien Berlin-Brandenburg OpTecBB e.V. wurde Ende Oktober ein neuer Vorstand gewählt. Vorstandsvorsitzender wurde bereits zum vierten Mal Prof. Dr. Günther Tränkle, Direktor des FBH; neu im Vorstand sind Peter Krause (Stellvertretender Vorsitzender), Martin Schell, Adrian Mahlkow und Gerrit Rössler. OpTecBB e.V. ist eine Initiative von Unternehmen und wissenschaftlichen Einrichtungen in Berlin und Brandenburg, die gemeinsame Wege zur Erschließung und Nutzung der Optischen Technologien und Mikrosystemtechnik gehen wollen. Der im Jahr 2000 gegründete Verein hat rund 100 institutionelle Mitglieder.

Frank van den Bogaart

Knighthood for Scientific Board Member Frank van den Bogaart
The FBH congratulates its long-term member of the Scientific Board Dr. Frank van den Bogaart. Dr. van den Bogaart was knighted in the Order of Oranje-Nassau by the Dutch King Willem-Alexander at the end of 2014. He received his royal honor for his achievements in the field of radar technology with particular focus on microwave monolithic integrated circuits.

Ritterwürde für Beiratsmitglied Frank van den Bogaart
Das FBH gratuliert seinem langjährigen Beiratsmitglied Dr. Frank van den Bogaart, der Ende 2014 in den Ritterstand von Oranje-Nassau erhoben wurde. Diese Ehre wurde ihm vom niederländischen König Willem-Alexander verliehen aufgrund seiner Errungenschaften auf dem Gebiet der Radartechnologie, insbesondere bei monolithisch-integrierten Mikrowellenschaltkreisen.

Manuela Urban, Managing Director of Forschungsverbund Berlin (FVB) presenting the challenge cup for the fastest FVB sports team at the Berlin company relay. FLTR: N. Hübener, N. Wolff, M. Greiner, M. Urban, K. Czajkowski, T. Filler, C. Stölmacker.

Manuela Urban, die Geschäftsführerin des Forschungsverbundes Berlin (FVB) überreicht den Wanderpokal für das schnellste FVB-Team beim Berliner Firmenlauf. V.l.n.r.: N. Hübener, N. Wolff, M. Greiner, M. Urban, K. Czajkowski, T. Filler, C. Stölmacker.

Sporting success

An FBH team comprising Nicolas Hübener, Christoph Stölmacker, and Nikolai Wolff has won the Adlershof company relay 2015 in the men's competitions. These runners, strengthened by Kamil Czajkowski, Thomas Filler, and Marcel Greiner, were also the fastest team of the Forschungsverbund at the Berlin company relay. Additionally, two FBH teams took part at the Airfield Run – with start and finish on the former airfield Tempelhof. Another team participated in the Team Half Marathon race around the Britzer Garden.

Sportlich erfolgreich

Das Team des FBH mit Nicolas Hübener, Christoph Stölmacker und Nikolai Wolff hat die Adlershofer Firmenstaffel 2015 bei den Herren über das ehemalige Flugfeld Johannistal gewonnen. Verstärkt durch Kamil Czajkowski, Thomas Filler und Marcel Greiner bildeten diese Läufer auch das schnellste Team des Forschungsverbundes beim Berliner Firmenlauf. Auch beim Airfield Run – mit Start und Ziel auf dem ehemaligen Flughafenfeld Tempelhof – waren zwei Mannschaften mit Mitarbeiterinnen und Mitarbeitern des FBH vertreten. Ein weiteres Team nahm am Mannschafts-Halbmarathon um den Britzer Garten teil.

Science Management
Wissenschaftsmanagement

Science Management – advice and services for research

The Science Management Department provides comprehensive advice and support to the Director as well as FBH scientists regarding projects and cooperation within networks. The main focus is on setting up industrial projects, obtaining project funding, and establishing R&D cooperation. FBH also plays a leading role in numerous regional, national as well as international networks and collaborative research projects, which are coordinated with support from the Science Management Department. The interdisciplinary team takes over administrative and non-scientific work during the application process of complex collaborative projects, the coordination of national and international projects, and their subsequent development and management. In addition, the Science Management Department ensures that processes in administration and IT support at the institute are handled smoothly.

With the newly created Prototype Engineering Lab, the FBH advances its research results by assembling modules up to the respective prototypes, designed for easy testing in the particular application field. The four-member team ensures that excellent research results will be transferred more rapidly into applications. FBH's components and modules have already been successfully integrated into systems and operationally demonstrated by using systematic, professional prototype engineering. In 2015, the first prototypes were successfully built and delivered to research and industrial partners.

The coordination of the Zwanzig20 consortium *Advanced UV for Life* is also a key activity of the department. The large consortium, currently consisting of 35 partners, is dealing with research, development and application of UV LED technology along the whole value chain – from the crystal up to its application in devices and systems, such as disinfection of drinking water. Only in 2015, twelve projects have been launched in this funding context; the institute is involved in six of them – partly in a leading role.

Another focus of the department is on securing skilled personnel in the high-tech sector. Thus, recruitment campaigns in natural sciences and technology occupy center stage within these activities. Established formats like the *6th Girls' Technology Congress* were continued in 2015 and, thanks to the participation in the EU consortium *GoPhoton!*, again internationally oriented. Also, the writing competition *LichtBlicke* was organized as part of the International Year of Light. The best contributions were set to music and presented at a concert.

For the first time, individual trainings between research institutions and companies were organized and carried out in a pilot project within the Photonics Cluster Berlin-Brandenburg. The positive participants' feedback will be used to promote a funding program for individual further training in high technology.

Wissenschaftsmanagement – Beratung und Dienstleistung für Forschung

Das Department Wissenschaftsmanagement berät und unterstützt die Institutsleitung sowie Wissenschaftlerinnen und Wissenschaftler am FBH umfassend bei Projekten und bei der Zusammenarbeit in Verbünden. Insbesondere bei der Anbahnung und Umsetzung von Industrieprojekten, Fördervorhaben sowie beim Aufbau von F&E-Kooperationen wird dieses Angebot gerne angenommen. Das FBH ist zudem federführend in zahlreichen regionalen, nationalen aber auch internationalen Netzwerken und Verbundforschungsvorhaben, die mit Unterstützung des Departments koordiniert werden. 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. Darüber hinaus sorgt das Department Wissenschaftsmanagement für reibungslose Abläufe in der Verwaltung und für den IT-Support im Institut.

Das neu geschaffene EntwicklungsZentrum entwickelt Forschungsergebnisse weiter, indem es Module bis hin zu Prototypen aufbaut, die so im jeweiligen Anwendungsfeld getestet werden können. Das vierköpfige Team sorgt dafür, dass Forschungsergebnisse des Instituts noch schneller in Applikationen überführt werden. Mit einem systematisierten Gerätebau werden die Komponenten und Module des FBH in Systeme integriert und einsatzfähig demonstriert. 2015 konnten erste Prototypen erfolgreich aufgebaut und an Forschungs- und Industriepartner geliefert werden.

Ein weiterer Schwerpunkt ist die Koordination des Zwanzig20-Konsortiums *Advanced UV for Life*. Das auf mittlerweile 35 Partner angewachsene Konsortium erforscht und entwickelt die UV-LED-Technologie entlang der kompletten Wertschöpfungskette bis hin zur Anwendung – vom Kristall bis zum Einsatz in Geräten wie etwa zur Desinfektion von Trinkwasser. Alleine 2015 sind zwölf Projekte in diesem Förderkontext angelaufen; das Institut ist in sechs dieser Vorhaben teilweise federführend eingebunden.

Ein weiterer Fokus der Abteilung liegt auf der Fachkräftesicherung im Hochtechnologie-Bereich. Bei diesen Aktivitäten stehen Nachwuchswerbung und -sicherung im naturwissenschaftlich-technischen Bereich im Mittelpunkt. 2015 wurden etablierte Formate wie der *Mädchen-Technik-Kongress* fortgeführt und dank der Mitwirkung im EU-Konsortium *GoPhoton!* weiterhin international ausgerichtet. Im Rahmen des Internationalen Jahrs des Lichts wurde auch der Schreibwettbewerb *LichtBlicke* organisiert. Die besten Beiträge wurden von einer Band vertont und bei der Abschlussveranstaltung im Rahmen eines Konzerts vorgetragen.

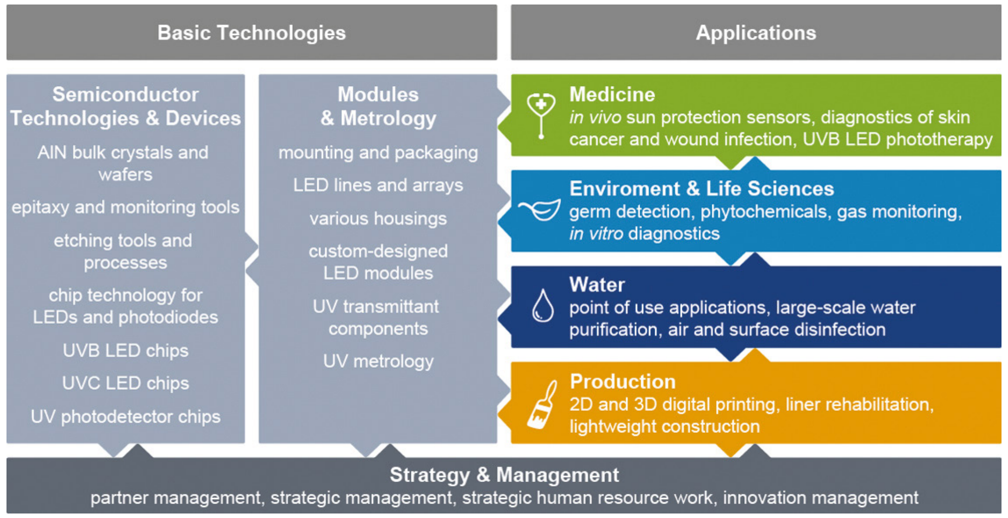
Im Zuge eines Pilotprojekts im Cluster Optik Berlin-Brandenburg wurden erstmalig individuelle Weiterbildungsmaßnahmen zwischen Forschungseinrichtungen und Unternehmen organisiert und durchgeführt. Das durchweg positive Feedback der Teilnehmenden wird nun genutzt, um ein Förderprogramm zur individuellen Qualifizierung im Hochtechnologiebereich zu entwickeln.

Advanced UV for Life – network management par excellence

ADVANCED UV FOR LIFE

The consortium *Advanced UV for Life* managed by FBH aims to develop UV LEDs that open up novel applications and expand existing ones for UV technology. 35 partners from science and industry along the entire value chain of UV LED technology are meanwhile involved in the BMBF-funded network, which is supported with up to 45 million € until 2019. Since many years, the FBH has been actively involved in comprehensive research activities that are targeted to advance UV LED technology. Many of them are, at least partially, funded within *Advanced UV for Life*. Results are presented in this report on p. 76 – an article dealing with degradation processes in long-lifetime UV-B LEDs – and on p. 78 regarding the development of UV-C LEDs for water disinfection. Further information can also be found in FBH's highlights on p. 23.

The coordination office of *Advanced UV for Life* has been successfully established in the Science Management Department at FBH. Management covers a wide range of activities aiming to develop sustainable organizational structures and to effectively benefit from synergies. To achieve this, the FBH develops efficient communication and cooperation processes. It supports interconnections of R&D activities and evaluates controlling and management tools by taking technology-related and market-based factors as well as the interdisciplinary competencies of the consortium partners into consideration. Moreover, communication processes are managed, informing the expert audience and also the general public about the aims and benefits of *Advanced UV for Life*.



Value chain of the *Advanced UV for Life* consortium.
Wertschöpfungskette des Konsortiums *Advanced UV for Life*.

As a common basis, a joint strategy has been successfully developed with the consortium partners. The coordination office manages the continuous strategy adjustments regarding market and technology developments and R&D results of the consortium.

Events and communication activities

In 2015, the coordination office organized 15 knowledge transfer events within the consortium, thus updating the joint strategy in the seven topic areas. Strategy, R&D results, and new projects have been evaluated at two events by *Advanced UV for Life's* advisory board. Furthermore, the coordination office staff assisted the consortium members in submitting their project proposals in time and according to the requirements of the BMBF.

Communication activities for the interested and expert audience have also been implemented. After the relaunch of the website www.advanced-uv.de, *Advanced UV for Life* not only appears in a new look, but also provides updated content including the English version and information about current and completed R&D projects. A communication concept for the consortium developed within a master thesis will be gradually implemented.

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

zwanzig20 PARTNERSCHAFT FÜR INNOVATION

'Applications of UV radiation – from skin treatment to drinking water disinfection' was the topic of a public panel discussion featuring partners of the consortium in February. It was jointly organized by Berliner Wirtschaftsgespräche e.V. and FBH. In November, *Advanced UV for Life* was represented at the micro photonics preview event by FBH together with the consortium partners micro resist technology GmbH and UV photonics NT GmbH, a start-up company of the FBH.

Advanced UV for Life – Netzwerkmanagement par excellence

Die Aktivitäten des vom FBH geleiteten Konsortiums *Advanced UV for Life* zielen darauf, die technische Entwicklung, die Verfügbarkeit und den Einsatz von UV-Leuchtdioden in breitem Maße voranzubringen. Aktuell arbeiten 35 Partner entlang der kompletten Wertschöpfungskette an der Entwicklung und Anwendung von UV-LEDs. Dafür stehen dem Konsortium, das im Rahmen des BMBF-Programms „Zwanzig20 – Partnerschaft für Innovation" gefördert wird, bis zu 45 Mio. € bis Ende 2019 zur Verfügung. Seit vielen Jahren entwickelt das FBH bereits die UV-LED-Technologie mit umfassenden F&E-Aktivitäten weiter. Etliche Projekte werden – mindestens teilweise – im Rahmen von *Advanced UV for Life* finanziert. Dieser Jahresbericht präsentiert Ergebnisse zu Degradationsprozessen in langlebigen UV-B-LEDs auf Seite 76 und zur Entwicklung von UV-C-LEDs für die Wasserdesinfektion auf Seite 78. Weitere Information finden sich zudem in den Schlaglichtern auf Seite 24. Die Koordinationsstelle von *Advanced UV for Life* ist im Department Wissenschaftsmanagement des FBH angesiedelt. Sie deckt vielfältige Aufgabenbereiche ab, mit denen nachhaltige Organisationsstrukturen entwickelt und Synergien innerhalb des Konsortiums optimal genutzt werden sollen. Zu diesem Zweck entwickelt das Team am FBH effiziente Kooperations- und Kommunikationsprozesse. Es unterstützt die Verzahnung von F&E-Tätigkeiten und erprobt geeignete Controlling- und Steuerungsinstrumente, wobei es sowohl technologie- und marktbezogene Faktoren als auch die interdisziplinären Kompetenzen der Konsortialpartner berücksichtigt. Darüber hinaus setzt die Koordinationsstelle Kommunikationsmaßnahmen um, mit denen das Fachpublikation und die allgemeine Öffentlichkeit über *Advanced UV for Life* informiert werden.

Grundlage für die Zusammenarbeit ist die gemeinsam mit den Konsortialpartnern entwickelte Strategie. Basierend auf Markt- und Technologieentwicklungen und den Ergebnissen der Forschungs- und Entwicklungsarbeiten des Konsortiums wird sie unter Federführung der Koordinationsstelle kontinuierlich weiterentwickelt.

Veranstaltungen und Kommunikationsmaßnahmen

Im Jahr 2015 hat die Koordinationsstelle 15 Veranstaltungen organisiert. Diese förderten nicht nur den Wissensaustausch innerhalb des Konsortiums, auch die Strategie in den sieben Themenfeldern wurde fortgeschrieben. Strategie, F&E-Ergebnisse und neue Projektideen wurden durch den Beirat von *Advanced UV for Life* begutachtet. Das FBH-Team unterstützte zudem die Mitglieder des Konsortiums bei der form- und fristgerechten Einreichung der Projektanträge.

2. Advisory Board Meeting of *Advanced UV for Life* in March 2015.
2. Beiratssitzung von *Advanced UV for Life* im März 2015.

Öffentlichkeitswirksame Maßnahmen fanden für die interessierte Allgemeinheit und das Fachpublikum statt. Ein wichtiger Baustein ist in diesem Zusammenhang die Webseite www.advanced-uv.de, die komplett überarbeitet wurde. Nun stehen alle Inhalte zweisprachig zur Verfügung, und Informationen über laufende und abgeschlossene Projekte sind abrufbar. Ein Kommunikationskonzept, das im Rahmen einer Masterarbeit für das Konsortium entwickelt wurde, wird schrittweise umgesetzt.

„UV-Strahlung nutzbar machen – von der Hautbehandlung bis zur Trinkwasserentkeimung" war das Thema einer öffentlichen Podiumsdiskussion. Sie wurde unter Beteiligung einzelner Konsortialpartner zusammen mit Berliner Wirtschaftsgespräche e.V. am FBH veranstaltet. Im November war das Konsortium auf dem micro photonics Preview Event in Berlin vertreten. Auf dem Stand stellten das FBH gemeinsam mit den Partnern micro resist technology GmbH und UV photonics NT GmbH, einer Ausgründung aus dem FBH, aus.

Prototype Engineering – further steps to systems capability and technology transfer

Fig. 1. UV-B LED module to trigger biosynthesis of plants.
Abb. 1. UV-B-LED-Modul zum Triggern der Biosynthese von Pflanzen.

With its newly created Prototype Engineering Lab, the Ferdinand-Braun-Institut ensures that excellent research results will be transferred more rapidly into market-oriented products, processes, and services. This way, the institute has established an active interface between business and science in 2014 that provides companies an easy access to state-of-the-art results. The FBH is thus taking the important step beyond the research module to the operational device. Easy-to-operate systems allow industrial and research partners to test FBH's R&D results in their applications and to prevail with product innovations in competitive markets.

Exemplary prototypes that demonstrate the commercialization of research results have already been implemented in previous projects. Based on these experiences, the Prototype Engineering Lab – as a pilot project – is currently assigned to the Science Management Department. The four-member team comprising a project and technology transfer manager, two electronics engineers, and a mechanical engineer has a period of three years to develop and test a sustainable business model.

Fig. 1 shows a current example for the integration of the institutes research results into a system to be applied in other specialist areas. Together with the Joint Lab GaN Optoelectronics, the Prototype Engineering Lab has developed a UV-B LED module for a research partner that positively influences biosynthesis during plant growth. With it, plants can be extensively irradiated with UV-B radiation of a specific wavelength (Fig. 2). FBH's UV-B LEDs feature a narrow emission spectrum, and the peak emission wavelength can be precisely adjusted to the most effective one. Thus, the biosynthesis of specific organic compounds can be triggered or intensified. The UV LEDs used in this special module are researched and developed at the FBH. Power supply, sensors, controllers, and laboratory electronics have been additionally integrated into the prototype, so that the LEDs are easy to handle for users and the device can be tested for the specific application.

The complex laboratory setup of a SERDS system – developed by colleagues of the Laser Sensors Lab – could be scaled down to a mobile device for on-site Raman spectroscopy to be utilized in an apple plantation. The programmable laser control and the battery-based power supply were integrated into a robust case, thus allowing flexible field measurements in agriculture (Fig. 5). Further solutions for application of novel research modules were developed and implemented in close collaboration with other FBH labs. Two exhibits (Fig. 3 and 4), for example, were constructed which illustrate the capability of diode laser modules developed by FBH's Laser Modules Lab.

The FBH is establishing its Prototype Engineering Lab with the help of the BMBF-funded *Veriplan* project – detached from individual applications and by involving all research areas of the institute. Furthermore, the institute tests the effective cooperation of its departments and labs with the Prototype Engineering Lab and expands its industry contacts to further extend technology transfer activities. A business model for the Prototype Engineering Lab and its team will be developed as well. Subsequently, the Prototype Engineering Lab will be established as an independently acting lab within FBH's III-V technology research area.

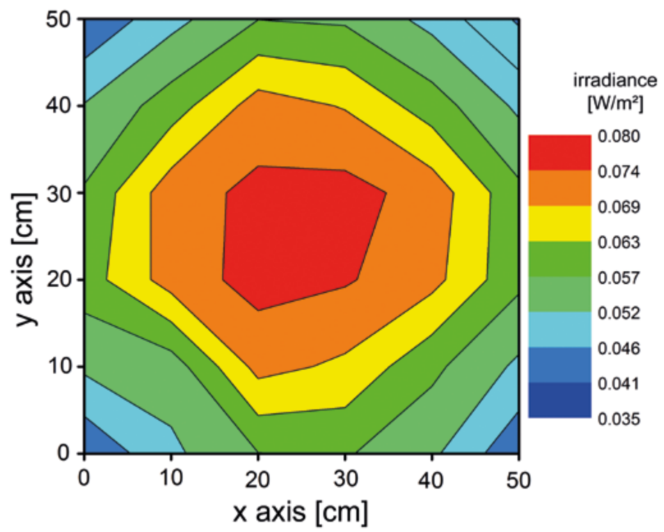


Fig. 2. Illumination of the usable area of the 309 nm UV-B LED module measured from a distance of 0.3 m.
Abb. 2. Ausleuchtung der Nutzfläche durch das 309 nm UV-B-LED-Modul in 0,3 m Abstand.

EntwicklungsZentrum – weitere Schritte zur Systemfähigkeit und zum Technologietransfer

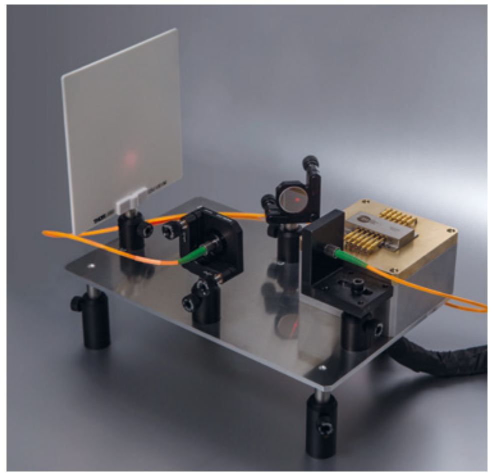


Fig. 3. Hologram column with hybrid integrated diode laser module.
Abb. 3. Hologrammsäule mit hybridem Diodenlaser-Modul.

Fig. 4. Demonstration of coherence of a hybrid laser module from the FBH.
Abb. 4. Demonstration der Kohärenz eines hybriden Lasermoduls aus dem FBH.

Mit seinem neu geschaffenen EntwicklungsZentrum sorgt das Ferdinand-Braun-Institut dafür, dass exzellente Forschungsergebnisse noch schneller in marktorientierte Produkte, Verfahren und Dienstleistungen überführt werden. Damit hat das Institut 2014 eine aktive Schnittstelle zwischen Wirtschaft und Wissenschaft geschaffen, die Unternehmen einen einfachen Zugang zu Ergebnissen auf dem aktuellen Stand der Forschung bietet. Folglich geht das FBH den wichtigen Schritt über das Forschungsmodul hinaus zum einsatzfähigen Gerät. Die hieraus entstehenden handhabbaren Systeme ermöglichen es Industrie- und Forschungspartnern, die F&E-Ergebnisse des FBH unkompliziert in ihren Anwendungen zu testen und mit Produktinnovationen konkurrenzfähig am Markt zu agieren.

Bereits in Vorläuferprojekten wurden exemplarische Prototypen zur Vermarktung der Forschungsergebnisse umgesetzt. Auf diesen Erfahrungen aufbauend, ist das EntwicklungsZentrum derzeit als Pilotprojekt an das Department Wissenschaftsmanagement angedockt. Das vierköpfige Team – eine Projektleiterin und Verwertungsmanagerin, zwei Elektronik-Ingenieure und ein Maschinenbau-Ingenieur – hat drei Jahre Zeit, ein tragfähiges Modell zu entwickeln und zu erproben.

Abb. 1 zeigt ein aktuelles Beispiel zur Integration von Forschungsergebnissen des Instituts in ein System zur Anwendung in anderen Fachdisziplinen. Das EntwicklungsZentrum hat hier zusammen mit dem Joint Lab GaN Optoelectronics ein UV-B-LED-Modul zur Pflanzenzucht für einen Forschungspartner entwickelt. Das Gerät ermöglicht die flächige Bestrahlung von Pflanzen mit UV-B-Strahlung spezifischer Wellenlänge (Abb. 2). UV-B-LEDs des FBH bieten ein schmalbandiges Emissionsspektrum und ihre zentrale Wellenlänge kann exakt auf die jeweils wirksamste abgestimmt werden. So kann etwa die Biosynthese spezieller Pflanzenwirkstoffe in Gang gesetzt oder intensiviert werden. Die UV-LEDs, die in dieses spezielle Modul eingebaut wurden, werden am FBH erforscht und entwickelt. Zusätzlich wurden in den Geräte-Prototypen Stromversorgung, Sensoren, Steuergeräte und Laborelektronik integriert, so dass die LEDs für die Anwender direkt handhabbar sind. Damit kann das Gerät für den spezifischen Anwendungsfall erprobt werden.

Für den Einsatz auf einer Apfelplantage konnte der komplexe Laboraufbau eines im Laser Sensors Lab entwickelten SERDS-Systems für die Vor-Ort-Ramanspektroskopie

Fig. 5. Mobile Raman system.
Abb. 5. Mobiles Raman-System.

in ein mobiles Gerät umgebaut werden. Die programmierbare Laseransteuerung und die Akku-basierte Stromversorgung fanden in einem robusten Koffer Platz, der eine flexible Feldmessung in der Landwirtschaft erlaubt (Abb. 5). Weitere Lösungen zur Anwendung von neuartigen Forschungsmodulen wurden in enger Zusammenarbeit mit anderen Labs des FBH entwickelt und umgesetzt. So wurden etwa zwei Messeexponate (Abb. 3 und 4) aufgebaut, die die Leistungsfähigkeit der Diodenlasermodule des Laser Modules Lab veranschaulichen.

Das FBH baut sein EntwicklungsZentrum im Rahmen des öffentlich finanzierten Pilotvorhabens *Veriplan* auf – losgelöst von Einzelanwendungen und unter Einbeziehung aller Forschungsbereiche des Instituts. Darüber hinaus testet das Institut die effektive Zusammenarbeit seiner Departments und Labs mit dem EntwicklungsZentrum und baut seine verwertungsrelevanten Kontakte zur Wirtschaft aus. Parallel wird ein Geschäftsmodell zur Finanzierung des Teams und des Zentrums nach Auslaufen der Förderung entwickelt. Danach soll das EntwicklungsZentrum als eigenständiges Prototype Engineering Lab im Forschungsbereich III/V-Technologie angesiedelt werden.

Securing skilled personnel in the photonics cluster in Berlin-Brandenburg

Photonics as one of the European key enabling technologies of the 21st century influences almost every aspect of our daily lives, but to most people the subject remains fairly unknown. To change that the UNESCO proclaimed 2015 as the *International Year of Light*.

The European Centres for Outreach in Photonics (ECOP) launched *GoPhoton!*, an EU-funded initiative through the FP7 program. FBH as member of this European consortium developed, implemented, and coordinated a series of outreach activities to inform about the wide spectrum of opportunities that photonics offers today's society. One of the highlights in 2015 was the *6th Girls' Technology Congress* for Berlin-Brandenburg, with special focus on photonics. On October 9, 125 girls from 7th to 12th grade took part in the photonics show with colorful physical and chemical experiments, the role-model presentation, and twelve workshops with hands-on experiments. Three of the workshops were offered by *GoPhoton!* partners from Barcelona, Brussels, and Galway in English language. In return, FBH's well-proven format of photonics' congresses for young people was transferred as 'good-practice' to seven other EU countries.

Professional musicians giving their best at the concert, the great final of the writing contest.
Professionelle Musiker im Einsatz beim großen Abschlusskonzert des Schreibwettbewerbes.

In addition to that, the writing contest *LichtBlicke* dedicated to photonics was imported from the research institute ICFO in Barcelona and launched in 2014. Students from schools in Berlin and Brandenburg had been asked to submit own texts dealing with light. Ten of them were selected, set to music and performed at the final concert on October 10, 2015 at the Mall of Berlin in conjunction with the *Festival of Lights* and *Berlin leuchtet*. A short concert video is available on youtube: https://www.youtube.com/watch?v=tDSrVUMuRPM. More than 400 interested youngsters, parents, and music fans joined the concert and learned a bit about photonics, too.

On October 13, 2015 *LIGHTtalks*, a special event organized by FBH in close co-operation with the Photonics Cluster Berlin-Brandenburg, focused on microsystems technology and optical sensor technology. The goal of the event was to raise awareness for the economic and industrial importance of photonics and its potential to create new innovation areas in existing businesses. The session was composed of a series of experienced speakers delivering talks that illustrate how to use the broad spectrum of photonic applications, thus bringing added value to industry.

Advanced vocational training and challenges for human resources development

Based on a survey conducted by the FBH on behalf of the Berlin Senate, the pilot project *beQual* (betriebliche Qualifizierung) offered several short training units for staff from companies and research institutions in the photonics cluster. 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. Conclusions and recommendations gained within *beQual* will be integrated in Berlin's political directives concerning further training.

AlFaClu (Altersgerechte und -übergreifende Fachkräfteentwicklung im Cluster Optik) is a research project funded by the Federal Ministry for Education and Research. It aims at developing adequate instruments and strategies for companies in the photonics cluster to meet the challenges concerning human resource development caused by demographic change and technological advancements. *AlFaClu* is an initiative of FBH and two universities from Hamburg in close cooperation with OpTecBB, the competence network for optical technologies and micro-system technology in the Berlin-Brandenburg region. Based on interviews with managing directors and HR managers several exigencies were identified, and a working group was established. A special industry forum (Wirtschaftsforum Treptow-Köpenick) was held at FBH in November 2015, informing both industry and the general public about latest research findings in photonics and their importance to our lives. The event also emphasized the necessity of close cooperation in outreach and HR development to guarantee well-qualified staff for the future.

Fachkräfte im Cluster Optik Berlin-Brandenburg sichern

Photonik ist eine der Schlüsseltechnologien des 21. Jahrhunderts, denn Licht und lichtbasierte Technologien beeinflussen fast alle Bereiche unseres täglichen Lebens. Jedoch ist sich dessen kaum jemand bewusst. Um dies zu ändern erklärte die UNESCO 2015 zum *Internationalen Jahr des Lichts*.

Die European Centres for Outreach in Photonics (ECOP) haben in diesem Zusammenhang *GoPhoton!*, eine durch das 7. Forschungsrahmenprogramm der EU finanzierte Initiative, ins Leben gerufen. Als Mitglied des europäischen Konsortiums entwickelte und koordinierte das FBH eine Reihe von Aktivitäten, die über Photonik informierten. Damit rückte es zugleich deren enormes Wachstumspotenzial und ihre vielfältigen Auswirkungen auf die Gesellschaft und unseren Alltag stärker ins Bewusstsein. Eines der Highlights 2015 war der *6. Mädchen-Technik-Kongress* mit dem Schwerpunkt Photonik. Am 9. Oktober erlebten 125 Mädchen der 7. bis 12. Klassen aus Berlin und Brandenburg eine farbenfrohe Licht-Show mit physikalischen und chemischen Experimenten, Präsentationen von Role-Models und 12 Workshops mit vielfältigen Möglichkeiten zum praktischen Ausprobieren. Drei der Workshops wurden von *GoPhoton!*-Partnern aus Barcelona, Brüssel und Galway auf Englisch angeboten. Im Gegenzug übernahmen die sieben Partnerländer das vom FBH erprobte und bewährte Konzept der Technik-Kongresse für Jugendliche.

Bereits 2014 wurde der Schreibwettbewerb *LichtBlicke*, ein „Good-Practice-Import" aus dem Institute of Photonic Sciences (ICFO), Barcelona, gestartet. Schülerinnen und Schüler aus Berlin und Brandenburg konnten Texte zum Thema Licht einreichen. Aus den

Zusendungen wurden zehn ausgewählt, die vertont und im Oktober zum Abschlusskonzert in der Mall of Berlin als Teil des *Festival of Lights* und *Berlin leuchtet*, aufgeführt wurden. Einen kleinen Einblick vermittelt das Video auf Youtube: https://www.youtube.com/watch?v=tDSrVUMuRPM. Über 400 Jugendliche, Eltern und Musikfans nahmen am Konzert teil und erfuhren nebenbei Interessantes rund um das Thema Licht.

Am 13. Oktober 2015 organisierte das FBH gemeinsam mit dem Cluster Optik Berlin-Brandenburg *LIGHTtalks*, einen speziellen Vortragsabend zu Mikrosystemtechnik und optischer Sensorik. Die Referenten verdeutlichten das breite Anwendungspotenzial von Lichttechnologien, zeigten neue Einsatzmöglichkeiten in industriellen Anwendungen auf und wie die Industrie von diesem Innovationspotenzial profitieren kann.

Industry forum: talks and discussions about challenges in human resource development. Wirtschaftsforum: Vorträge und Diskussionen über die anstehenden Herausforderungen bei der Personalentwicklung.

Weiterbildung und Anforderungen an die Personalentwicklung

Eine Untersuchung zum Weiterbildungsbedarf im Cluster Optik, die das FBH zuvor im Auftrag der Senatsverwaltung für Wirtschaft, Technologie und Forschung durchgeführt hatte, ergab einen Bedarf an maßgeschneiderten Weiterbildungsangeboten über klassische Formate hinaus. Darauf aufbauend hat das FBH im Rahmen des Pilotprojekts *beQual* (betriebliche Qualifizierung) spezielle Trainingseinheiten für Mitarbeiterinnen und Mitarbeiter von Unternehmen und Instituten entwickelt und getestet. Diese richteten sich meist an Einzelpersonen, dauerten in der Regel nur ein bis zwei Tage und bezogen sowohl die vorhandene Infrastruktur als auch das Know-how der Beschäftigten von Forschungseinrichtungen mit ein. Erkenntnisse und Empfehlungen aus *beQual* werden in die künftigen Förderrichtlinien der Senatsverwaltung einfließen.

Das vom BMBF geförderte Forschungsprojekt *AlFaClu* (Altersgerechte und -übergreifende Fachkräfteentwicklung im Cluster Optik) beschäftigt sich mit den Herausforderungen an die Personalentwicklung angesichts des demografischen Wandels und technologischer Weiterentwicklungen. Im Projekt sollen passende Instrumente für das Kompetenzmanagement entwickelt und getestet werden. *AlFaClu* ist eine Initiative des FBH und zweier Universitäten in Hamburg in enger Kooperation mit OpTecBB e.V., dem Kompetenznetz für Optische Technologien und Mikrosystemtechnik in Berlin-Brandenburg. Durch Interviews mit Geschäftsführern und Personalverantwortlichen wurden verschiedene Handlungsfelder identifiziert und ein Arbeitskreis *Fachkräfte im Cluster* ins Leben gerufen. Unter dem Titel „Fachkräftesicherung im Cluster Optik – (k)ein Problem?" fand zudem im November 2015 am FBH das Wirtschaftsforum Treptow-Köpenick statt. Dabei wurden nicht nur aktuelle Forschungsergebnisse vorgestellt, sondern vor allem die Notwendigkeit von engerer Vernetzung und Kooperation zur Fachkräftesicherung unterstrichen.

Science Management Wissenschaftsmanagement

Photonics
Photonik

Photonik

Im Forschungsbereich Photonik deckt das FBH ein breites Spektrum an Entwicklungen zu Diodenlasern und Leuchtdioden (LEDs) ab, die auf die jeweilige Anforderung zugeschnitten werden. Das Portfolio umfasst Galliumarsenid-basierte Diodenlaser, die vom infraroten bis zum ultravioletten Spektralbereich emittieren, sowie Laserdioden und LEDs auf Galliumnitrid-Basis, die im UV-Spektralbereich abstrahlen. Aktuell setzt das FBH die folgenden Schwerpunkte:

- ***Hochleistungs-Diodenlaser*** – Breitstreifenlaser, Laserbarren und Stacks, optimiert auf hohe Ausgangsleistungen. Sie werden u.a. als Pumplaser und für die direkte Materialbearbeitung genutzt.
- ***Lasermodule*** – in die miniaturisierten Module werden Optiken zur Strahlformung, externe Resonatoren, Elektronik und frequenzverdoppelnde Kristalle hochpräzise integriert. Auch die anschließende Kopplung in Glasfasern ist möglich. Sie eignen sich u.a. für den Einsatz in Displays oder der Medizintechnik.
- ***Lasersensorik*** – Diodenlaser, die speziell auf Anwendungen in der Sensorik und der Analytik zugeschnitten sind. Sie kommen u.a. in miniaturisierten, portablen Lasermesssystemen zum Einsatz, die Messungen von Raman-Spektren auch in stark fluoreszierenden Umgebungen ermöglichen.
- ***Lasermetrologie*** – in diesem Bereich werden ultra-schmalbandige Diodenlasermodule entwickelt. Dank der Hochpräzisionsmontage sind sie besonders kompakt und robust und eignen sich daher auch für Weltraumanwendungen.
- ***GaN-Optoelektronik*** – auf diesem Gebiet entwickelt das FBH Nitrid-Laserdioden und UV-Leuchtdioden, insbesondere für den UV-B- und UV-C-Spektralbereich. Die LEDs eigenen sich u.a. für die Oberflächenbehandlung und die Pflanzenbeleuchtung.

Das erforderliche grundlegende Know-how hält das Department Optoelektronik bereit. Es entwirft, realisiert und charakterisiert die zugehörigen Diodenlaser-Chips.

Photonics

Within its photonics research area, FBH covers a broad range of diode laser and LED developments that are tailored precisely to fit individual requirements. The portfolio comprises gallium arsenide based diode lasers, emitting from the infrared to the UV spectral range, as well as laser diodes and LEDs based on gallium nitride with emission in the UV spectral range. The FBH currently focuses on the following topics:

- ***High-power diode lasers*** – broad area lasers, laser bars, and stacks optimized for high output powers. They are used as pump lasers as well as for direct materials processing.
- ***Laser modules*** – optics for beam shaping, external resonators, electronics, and crystals for frequency doubling are integrated into the miniaturized laser modules. Even subsequent coupling into glass fibers is possible. These light sources are ideally suited for applications including displays and medical technology.
- ***Laser sensors*** – diode lasers that are customized for applications in sensors and analytics. They are employed, e.g., in miniaturized, portable laser measurement systems enabling to measure Raman spectra even in highly fluorescent environments.
- ***Laser metrology*** – ultra-narrowband diode laser modules are developed in this field. Due to high-precision mounting they are particularly compact as well as robust and thus perfectly suited for space applications.
- ***GaN optoelectronics*** – FBH develops nitride laser diodes and UV light-emitting diodes (LED) especially for the UV-B and UV-C spectral range. Applications eligible for LEDs include surface treatment and plant illumination.

The required basic know-how for these developments is provided by the Optoelectronics Department. It designs, realizes, and characterizes the corresponding diode laser chips.

Understanding and addressing the limits to direct diode laser systems: improved radiance in high-power broad area diode lasers via suppression of lateral carrier accumulation

The radiance of a laser light source is a key figure that determines its application in science and industry. It is defined as power density $B = P_{opt}/(A^*\Omega)$, with P_{opt}, A and Ω denoting the optical output power, the emitter area, and the laser beam solid angle, respectively. The materials processing industry demands laser systems with high radiance at high conversion efficiency for the use in, e.g., sheet metal cutting or welding. Today's state-of-the-art systems use diode-pumped solid-state disc and fiber lasers which deliver high radiance but are limited to conversion efficiencies of ≤ 40 %. In order to further increase the conversion efficiency of industry-class laser systems for sheet metal cutting, the direct use of diode laser radiation is necessary.

High-power broad area (BA) diode lasers emitting in the near-infrared range deliver high output powers at efficiencies better than 65 %. Furthermore, they are easy to integrate due to their compactness, and they can be fabricated using low-cost mass manufacturing techniques. In the case of edge-emitting diode lasers, the radiance is dominated by the linear radiance $B_{lin} = P_{opt}/BPP_{lat}$. Here, the lateral (in-plane) beam parameter product is defined as $BPP_{lat} = 0.25^*\Theta_{95\%}^*w_{95\%}$, with $\Theta_{95\%}$ and $w_{95\%}$ denoting lateral far field angle and near field waist at 95 % power content. Unfortunately, the large BPP_{lat} observed in BA lasers limits the linear radiance and is the main obstacle preventing higher powers from being obtained in direct diode laser systems. Therefore, the High-Power Diode Laser Lab at FBH is pursuing a series of experimental studies that seek to isolate and identify the most influential effects on the BA laser BPP_{lat}. These studies make use of FBH in-house III-V resources, including epitaxy, processing, and assembly. The studies focus on diode lasers with a standard commercial configuration, featuring 90 µm stripe width and 4 mm resonator length. Exemplary chips are shown in Fig. 1, which illustrates broad area lasers soldered to CuW carriers for testing in the laboratory.

Fig. 1. FBH standard test format: broad area lasers (L = 4 mm, w = 90 µm) soldered with AuSn onto CuW screening submounts for cw testing at T_{HS} = 25°C.

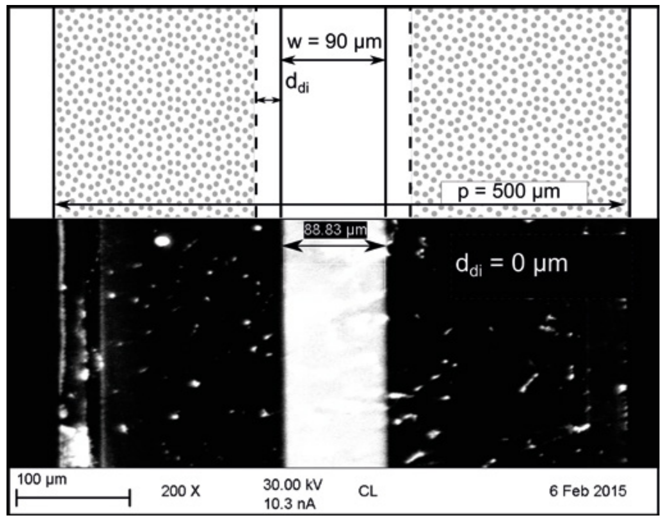


Fig. 2. Mask layout and CL imaging of deeply implanted broad area emitters. Top: Outline of lateral chip design with w = 90 µm injection stripe, chip width p and deep implantation distance d_{di}. Bottom: Plan view CL image via substrate at d_{di} = 0 µm shows that light emission in the edges is successfully suppressed.

Most recently, the impact of the lateral carrier profile was investigated, specifically the influence of excess carriers accumulating at the edges of broad area stripes, which have been proposed as playing a major role in limiting BPP_{lat}. In order to control this phenomenon, protons are deeply implanted through the active area, making use of two important effects of implantation. First, the current injection into the edge region is blocked (implanted material is highly resistive) and second, carriers that diffuse into this region are rapidly lost (rapid non-radiative recombination centers are created). As a result, the accumulation of carriers is strongly reduced in the proton-irradiated areas (see Fig. 2). Then, the influence of accumulated carriers was tested by using variation in the lateral distance d_{di} of the proton-irradiation from the stripe edge as a diagnostic tool.

As indicated in Fig. 3, the impact of the implantation at d_{di} = 10 µm is negligible, with efficiency, power, and BPP_{lat} curve unchanged compared to reference devices. Hence, all important carrier effects are limited to a 10 µm broad zone beyond the stripe edge. However, the close implantation at d_{di} = 0 µm reduces the conversion efficiency by 7 % at P_{opt} = 7 W, indicating that damage-induced losses due to non-radiative processes are occurring. The effect of deep proton implantation through the active area on the lateral beam quality can be seen in Fig. 4. While the d_{di} = 10 µm implanted devices show no change in BPP_{lat}, the devices with close implantation at d_{di} = 0 µm have an improved in-plane beam quality for all measured output powers, yielding BPP_{lat} = 2 mm×mrad at an output power of P_{opt} = 7 W. This results in a linear brightness of B_{lin} = 3.5 W/ mm×mrad, which is the highest value reported for B_{lin} for BA lasers with stripe widths in the 90...100 µm range. In conclusion, it was shown that lateral carrier accumulation is an important effect that regulates the BPP_{lat} in BA lasers, being responsible for ~ 1/3 of the increase in BPP_{lat} with bias. Ongoing research at the FBH is seeking alternative techniques for suppressing this effect without compromising the efficiency. Detailed studies into the remaining factors limiting B_{lin} are also continuing.

This work was supported by Trumpf Photonics Inc., Cranbury, NJ, USA.

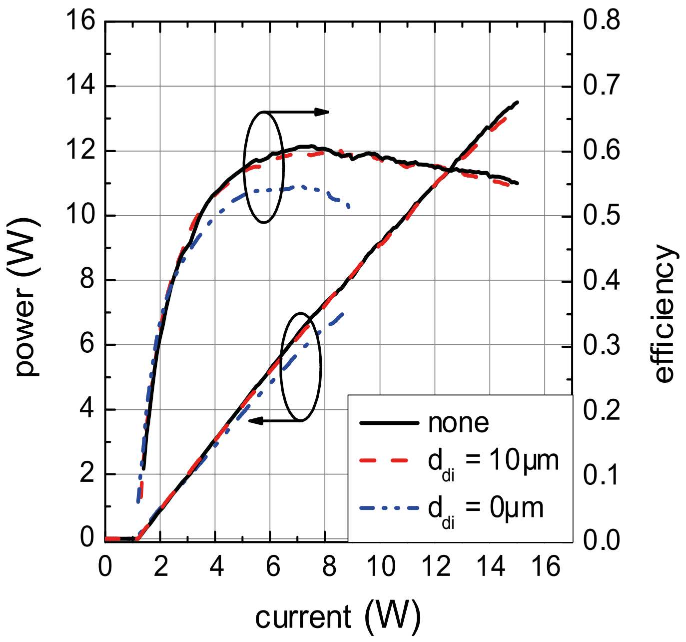


Fig. 3. Optical output power and conversion efficiency versus current for broad area devices with w = 90 µm and λ = 969 nm with various lateral implantation profiles.

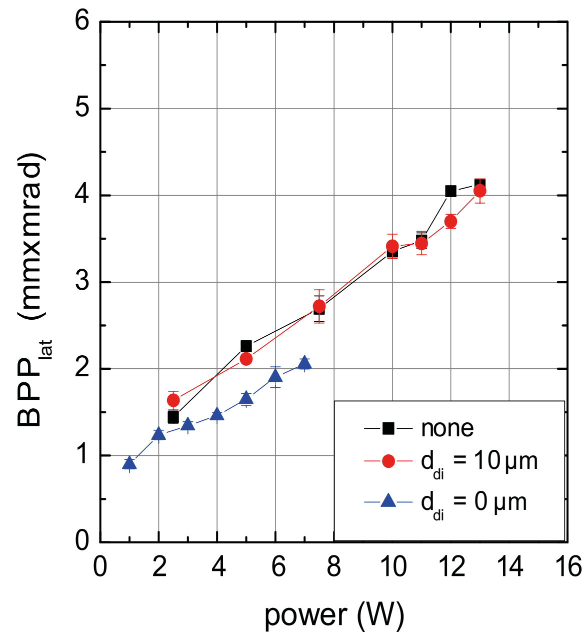


Fig. 4. The lateral beam parameter product BPP_{lat} as function of power shows significant reduction to 2 mm×mrad at P_{opt} = 7 W for lasers with d_{di} = 0 µm, yielding very high brightness of B_{lin} = 3.5 W/mm×mrad.

Lasersysteme, die in der Materialbearbeitung eingesetzt werden, müssen hohe Strahldichten bei gleichzeitig hoher Effizienz liefern. Daher zielt die industrienahe Forschung in diesem Bereich auf die Verbesserung der lateralen Strahlqualität von hocheffizienten Breitstreifen-Diodenlasern. Am FBH wurde ein wichtiger Effekt identifiziert, der die laterale Strahlqualität verschlechtert. Die Ansammlung von Ladungsträgern am Rand des Injektionsstreifens steigert den Gewinn für laterale Moden höherer Ordnung und erhöht somit das Strahlparameterprodukt. Weiterhin konnte dieser Effekt mithilfe von tiefer Protonen-Implantation unterdrückt werden, auf Kosten eines Effizienzverlusts von 7 %. Auf diese Weise wurde eine lineare Strahldichte von B_{lin} = 3,5 W/mm×mrad erzielt, was in der vorliegenden Konfiguration (L = 4 mm, w = 90 µm) einen Welt-Bestwert darstellt. Weitere Aktivitäten zielen darauf, eine zu Technik finden, die eine Ladungsträger-Ansammlung verhindert, ohne die Effizienz zu beeinträchtigen.

Publications

M. Winterfeldt, P. Crump, S. Knigge, A. Maaßdorf, U. Zeimer, G. Erbert, "High beam quality in broad area lasers via suppression of lateral carrier accumulation", IEEE Photon. Tech. Lett., Vol. 27, No. 17, 1809 (2015).

M. Winterfeldt, P. Crump, S. Knigge, A. Maaßdorf, G. Erbert, "Increased slow-axis beam quality in 9xx nm high power broad area diode lasers by modifying the lateral current profile at the device edges", Conf. on Lasers and Electro-Optics/Europe (CLEO/Europe), Jun. 21-25, Munich, Germany, paper CB_P_5 (2015).

Record value for lateral brightness > 6 W/mm×mrad from narrow-stripe broad area diode lasers, for the next generation of brilliant direct diode laser systems

Incoherent optical beam combining of multiple broad area (BA) diode laser single emitters enables the output power of fiber-coupled direct diode laser systems to be scaled into the kW range. However, the lateral brightness $B = P/BPP$ of these systems is ultimately limited by the optical output power P and the in-plane beam parameter product $BPP = ¼\ W_{95\%} \times \Theta_{95\%}$ of the single emitters ($W_{95\%}$,$\Theta_{95\%}$ are width and angle at 95 % power). Specifically, the maximum optical power that can be coupled into a fiber of fixed numerical aperture and core diameter is directly proportional to the brightness of the respective single emitters. State-of-the-art commercial single emitters with 100 µm emission apertures operate with *BPP* of 3…4 mm×mrad at optical output powers P ~ 10 W for overall B ≈ 3 W/mm×mrad. Single emitters with increased *B*, achieved for example by reducing the *BPP* at high output power, are of major interest for many applications that require both high power and high brightness, such as sheet metal cutting or additive manufacturing.

The FBH is developing diode laser sources with increased lateral brightness, for example within the EU project *BRIDLE* (www.bridle.eu), and several technological approaches are followed [4]. One direct technique for scaling the linear brightness of diode lasers is to narrow the contact stripe width of the BA emitter from a typical 90 - 100 µm down to 20 - 30 µm to cut off higher order lateral modes and reduce the *BPP*. Detailed reports on narrow-stripe broad area lasers (NBA lasers) with 30 µm apertures were presented by the FBH early in 2015, confirming an enhancement of overall *B* [4,3]. However, the net benefit is limited by the increased impact of lateral carrier accumulation (LCA) at the device edges. In conventional gain-guided BA diode lasers, current spreading occurs in the p-side and a proportion of carriers is lost at the device edges, limiting overall efficiency. In addition, as bias increases, the number of carriers in the device edges rises. The resulting LCA at the stripe edges provides gain for higher order lateral modes that have wide near fields and high *BPP*, leading to degradation in *B*. As stripe width is reduced, efficiency loss due to current spreading and brightness degradation due to LCA become major limits to performance. Thus, further enhancements in lateral brightness are being sought by combining even narrower (20 µm) stripe widths with a lateral current barrier at the edges of the stripe, building on parallel studies of devices with 90 µm stripe width.

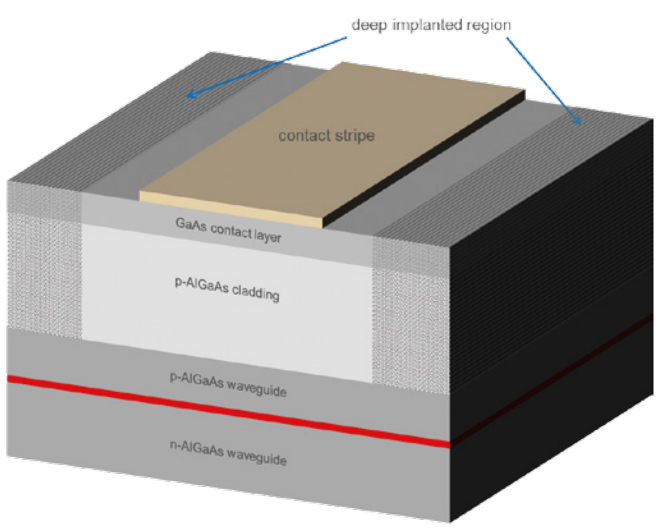


Fig. 1. Schematic illustration of narrow stripe broad area emitters with deep implanted current barriers at the edges of the contact stripe, as developed within the *BRIDLE* project.

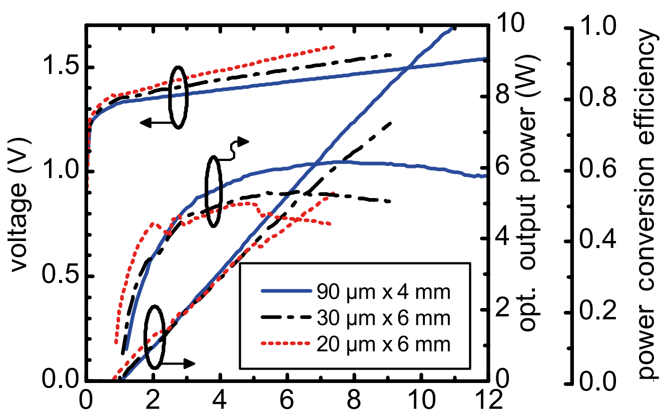


Fig. 2. Efficiency, voltage and optical output power of broad area emitters with different stripe geometries at λ = 975 nm.

Both approaches were combined in recent studies at the FBH of NBA lasers [2,1] with lateral current barriers. Following previous work [4, 3], high power and high conversion efficiency were sustained in these small area structures by using (FBH patented) extreme double-asymmetric vertical epitaxial layer structures, which use very thin p-side waveguide layers for low electrical resistance and minimal power saturation at high bias. Lateral current barriers were realized via a deep He^+ implantation close to the stripe, as schematically illustrated in Fig. 1. The deep implantation creates vacancies in the semiconductor and increases the electrical resistivity, suppressing current flow to the device edges. In these first trials of NBA lasers, the resistive region halted at a depth of 0.8 µm above the active region. After all processing was complete, FBH facet passivation was used to ensure reliable operation at high power densities. For device testing, single emitters were mounted p-side down on CuW carriers (with 4 mm and 6 mm resonator length, for conventional BA and NBA lasers respectively). Measurements of the light-current characteristics, spectra and beam quality were carried out at T = 20°C under continuous wave operation.

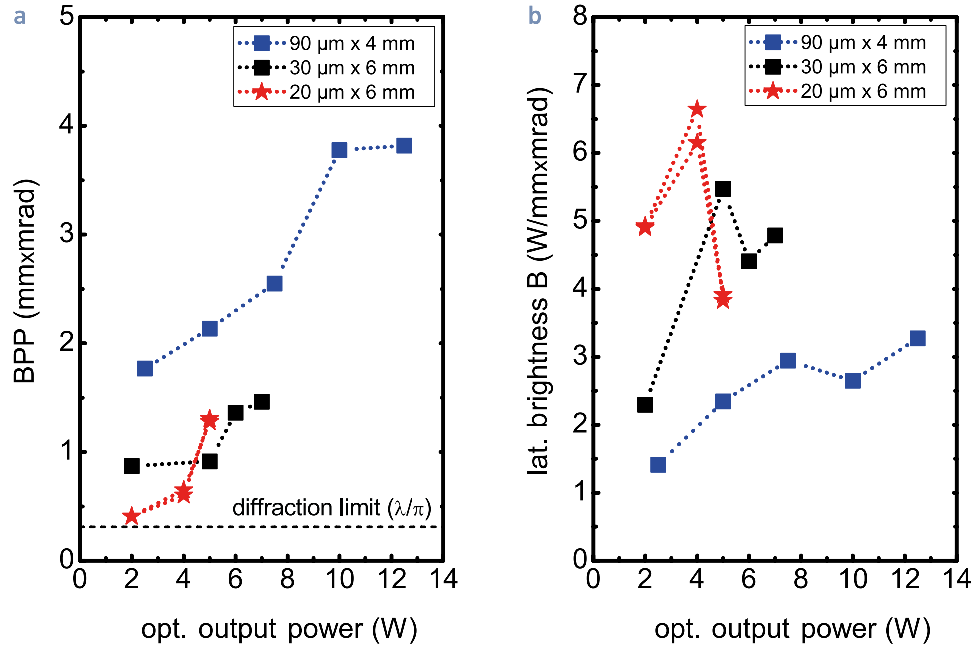


Fig. 3. BPP (a) and lateral brightness (b) as a function of output power for broad area emitters with different stripe geometries at λ = 970 nm.

Fig. 2 shows the light-current characteristics of broad area emitters with varied stripe width and implantation. As discussed above, the NBA laser devices (20 µm, 30 µm stripes) maintain reasonable power and conversion efficiency, although these remain reduced compared to conventional 90 µm stripe devices. Fig. 3a shows *BPP* for the corresponding devices as a function of output power, which is a factor of > 2x improved in NBA lasers at an equivalent power level. Therefore, a large net benefit in lateral brightness is observed (Fig. 3b), with the maximum linear brightness achieved for 20 µm wide emitters. These operate with peak B > 6 W/mm×mrad at P = 4 W where conversion efficiency is ≈ 50 %, a peak brightness twice that of reference 90 µm stripe devices that show peak B ~ 3.5 W/mm×mrad at P ~ 13 W (~ 60 % efficiency). This performance is enabled via use of advanced designs and technology for vertical and lateral structures, and advanced facet technology. Performance enhancements are currently sought using further improved lateral and vertical designs.

This work was supported by the European Commission within the *BRIDLE* program (7th FP) under Grant 314719.

Publications

[1] P. Crump, M. Winterfeldt, J. Decker, M. Ekterai, J. Fricke, S. Knigge, A. Maaßdorf, G. Erbert, "Novel approaches to increasing the brightness of broad area lasers" Proc. SPIE 9767, Photonics West, San Francisco, USA, Feb. 13-18, 97671L (2016) (Invited).

[2] J. Decker, M. Winterfeldt, J. Fricke, A. Maaßdorf, P. Crump, "Study of lateral brightness in 20 µm to 50 µm wide narrow stripe broad area lasers", Proceedings of 2015 High Power Diode Lasers and Systems Conference (HPD), Oct.14-15, ISBN 978-1-4673-9177-1, pp. 21-22 (2015).

[3] J. Decker, P. Crump, J. Fricke, A. Maaßdorf, G. Erbert, G. Tränkle, "High brightness narrow-stripe broad-area lasers with 7 W optical output at 910, 935 & 970 nm for coarse spectral beam combining", CLEO Europe, Jun. 21-25, Munich, Germany, ISBN: 978-1-4673-7475-0 (2015).

[4] P. Crump, J. Decker, M. Winterfeldt, J. Fricke, A. Maaßdorf, G. Erbert, G. Tränkle, "Development of high-power diode lasers with beam parameter product below 2 mm×mrad within the BRIDLE project", Proceedings of SPIE 9348, Feb. 07-12, 93480D (2015).

Laser mit Ausgangsleistungen im kW-Bereich spielen eine wichtige Rolle in der Materialbearbeitung. Die Kernkomponente solcher Lasersysteme besteht aus mehreren einzelnen Breitstreifenlasern, deren Strahlung mittels inkohärenter optischer Strahlkombinierung gebündelt wird. Je nach erforderlicher Strahlqualität wird diese Strahlung direkt oder als Pumpquelle für Faser- oder Festkörperlaser genutzt. Im Rahmen des EU-Projekts *BRIDLE* erarbeitet das FBH die Grundlagen für Diodenlaser mit deutlich höherer Strahldichte. Das FBH designt, prozessiert und charakterisiert die entsprechenden Chips. Diese Breitstreifenlaser zeichnen sich durch einen schmalen Kontaktstreifen (W = 20 µm) und Strombarrieren neben dem Kontaktstreifen aus. Diese werden mittels tiefer Edelgasimplantation erzeugt, um die laterale Stromverbreiterung einzudämmen. Beide Maßnahmen reduzieren das laterale Strahlparameterprodukt *BPP* signifikant, sodass ein Rekordwert für die laterale Strahldichte – dem Verhältnis von Ausgangsleistung zu *BPP* – von > 6 W/mm×mrad für Breitstreifenlaser erreicht wurde. Die Chips erreichen die maximale Strahldichte bei 4 W Ausgangsleistung und einem Wirkungsgrad von 50 %.

Compact single-mode fiber-coupled modules in the multi-watt power range – promising laser light sources for pumping applications

Applications like pumping of solid-state lasers and frequency conversion require efficient and compact laser light sources. Such laser devices must provide spectrally narrow-band near-infrared (NIR) radiation in continuous-wave (cw) operation at high output powers in a spatially fundamental mode. A distributed Bragg reflector (DBR) tapered diode laser is well-suited to fulfill these requirements. However, this diode laser type is characterized by an astigmatic beam, properties of which change slightly in dependence on the output power. It is therefore challenging to use this particular laser light source at variable output powers. Over the past three years, the Ferdinand-Braun-Institut (FBH) has collaborated with FCC FibreCableConnect, C2GO inprocess solutions, and eagleyard Photonics within the InnoProfile-Transfer joint research project *FaBriDi* in order to develop fiber-coupled demonstrators for unrestricted industrial use, as presented in Fig. 1, based on DBR tapered diode lasers. Aim of the now successfully completed project was to maintain the high spectral brightness and to simplify the use of these diode lasers.

Initially, the FBH investigated beam shaping and subsequent single-mode fiber (SMF) coupling of DBR tapered diode laser radiation in a bench-top experiment. Particularly interesting in this context was the influence of the injection current into the taper section on the diode laser beam properties and the coupling performance. Measurements were conducted at a fixed optical lens configuration, which was optimized for the maximum applied taper current. At this current value a maximum optical power ex SMF of 3.5 W was reached at a coupling efficiency of 67 %. As depicted in Fig. 2, with decreasing taper current the optical power ex SMF decreased nonlinearly due to gradual defocusing of the laser beam in the slow axis. This behavior is induced by an altering value of the beam astigmatism as a function of the taper current, which is characteristic for diode lasers and amplifiers with a tapered gain section. During coupling experiments, arbitrary changes in the single-frequency operation of the DBR tapered diode laser were observed, as can be seen in Fig. 3 (b), which was attributed to optical feedback. However, the optical spectrum remained within 0.4 nm at all times. A stigmatic, nearly Gaussian laser beam was obtained behind the SMF, and the results of the corresponding beam quality measurements were independent of the transversal direction (fast or slow axis) as well as of the applied taper current.

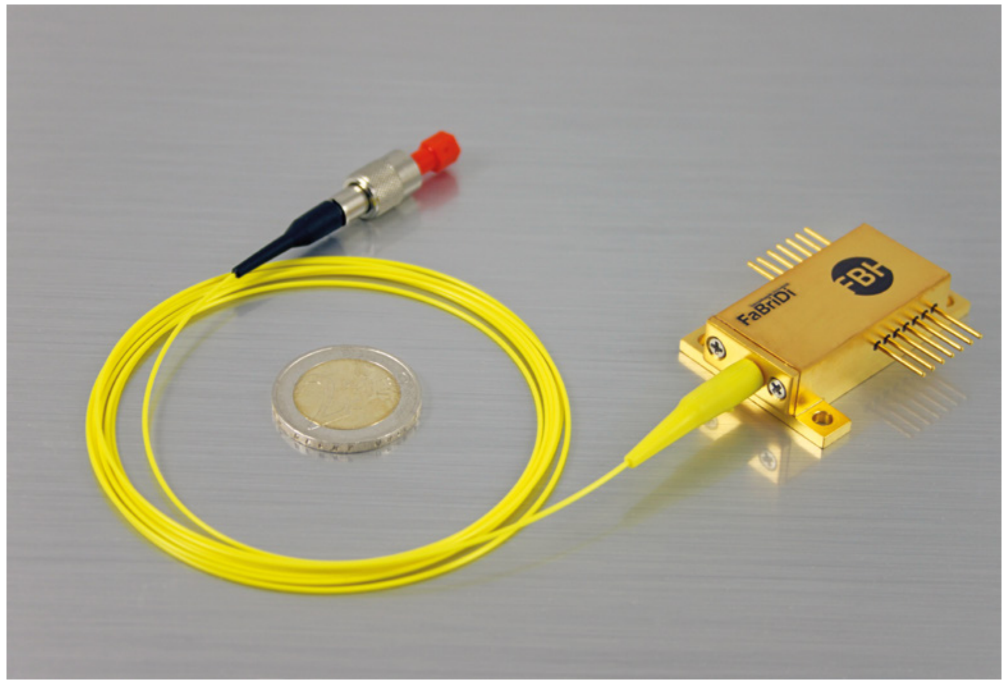


Fig. 1. Butterfly module with single-mode fiber output.

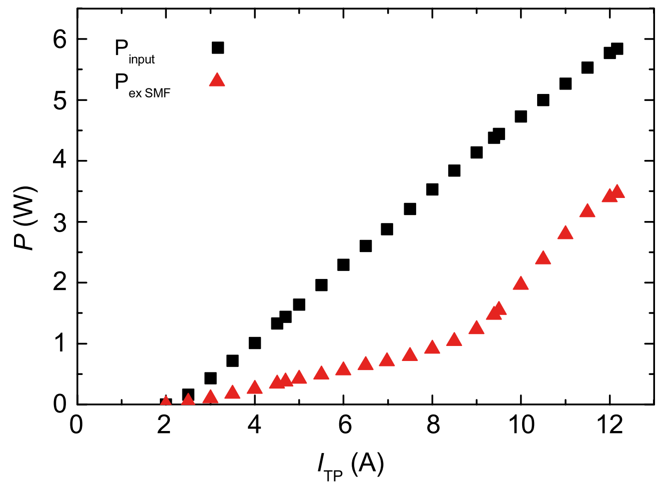


Fig. 2. Optical power in front and behind the SMF vs. taper current measured in a bench-top experiment.

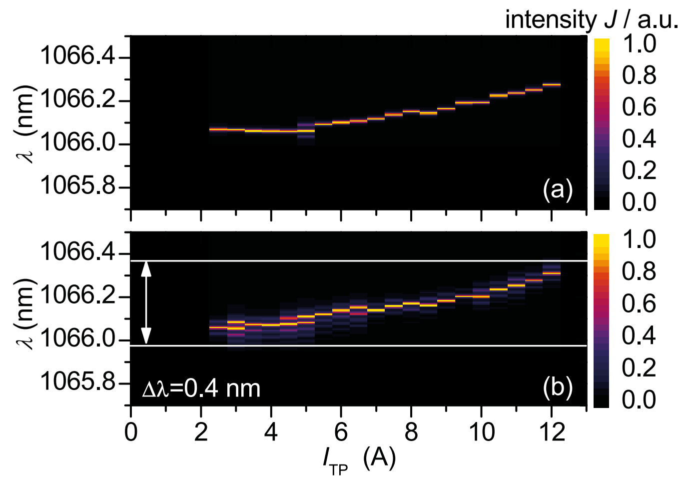


Fig. 3. Optical spectrum before (a) and during (b) coupling experiments vs. taper current measured in a bench-top experiment.

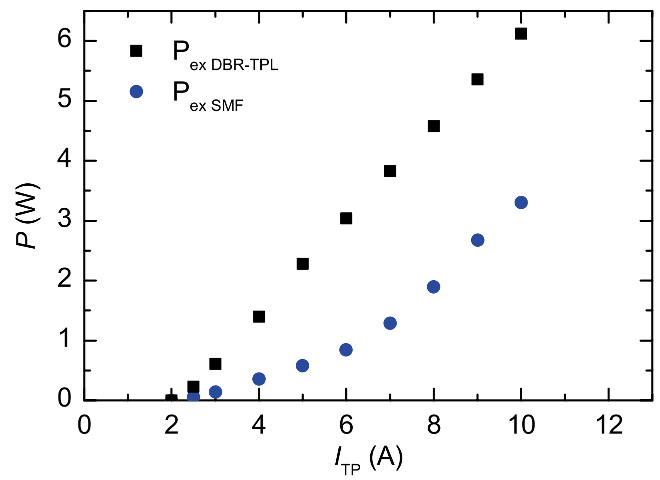


Fig. 4. Optical power ex DBR tapered diode laser and ex SMF vs. taper current in the assembled micro-module.

Based on these findings, a fiber-coupled demonstrator as shown in Fig. 1 has been developed in close collaboration with the project partners. It comprises a highly brilliant DBR tapered diode laser emitting around 1064 nm and a micro-optical assembly designed to maintain brightness and mounted with sub-micrometer precision. It also contains temperature-stabilizing components and an SMF with a core diameter of 6 µm along with a standard FC/APC connector. With this assembly, an optical power ex SMF of more than 3 W at a coupling efficiency of nearly 60 % has been achieved up to date, as depicted in Fig. 4. Small changes in the emission spectrum of the DBR tapered diode laser with increasing optical power are characteristic for this fiber-coupled module due to optical feedback. As expected, a stigmatic and nearly Gaussian laser beam is available behind the SMF regardless of the operating power level.

This work was funded by the German Federal Ministry of Education and Research under contract No. 03IPT613A.

Zum Pumpen von Festkörper- und Faserlasern sowie für die Frequenzkonversion werden effiziente Hochleistungslaser benötigt. Diese müssen im Dauerstrichbetrieb eine räumlich beugungsbegrenzte und spektral schmalbandige Strahlung im nahen infraroten Spektralbereich emittieren. Im Rahmen des nunmehr erfolgreich abgeschlossenen InnoProfile-Transfer-Projekts *FaBriDi* hat das Ferdinand-Braun-Institut ein Konzept erarbeitet, mit dem sich die Strahlung von DBR-Trapezlasern formen und anschließend in eine Single-Mode-Faser (SMF) einkoppeln lässt. In enger Zusammenarbeit mit den Projektpartnern wurden anschließend kompakte Diodenlasermodule mit einem SMF-Ausgang entwickelt, die einen stigmatischen und beinahe beugungsbegrenzten Strahl mit einer Ausgangsleistung von mehr als 3 Watt liefern.

Publications

D. Jedrzejczyk, P. Asbahr, M. Pulka, B. Eppich, K. Paschke, "Injection current dependent single-mode fiber coupling of a DBR tapered diode laser beam", IEEE Photon. Techn. Lett., vol. 28, no. 8, pp. 876-879 (2016).

D. Jedrzejczyk, A. Sahm, C. Carstens, G. Urban, M. Pulka, B. Eppich, F. Scholz, K. Paschke, "Coupling of a high-power tapered diode laser beam into a single-mode-fiber within a compact module", SPIE Proc. 9348, 93480Z (2015).

Array with 24 distributed Bragg reflector lasers for miniaturized optical systems

Arrays consisting of small linewidth emitters with defined positions and frequencies are attractive light sources for optical systems like three-dimensional (3D) scanners used, e.g., for reprography or rapid prototyping. Because of their small dimensions and high conversion efficiencies, diode lasers are particularly well-suited to miniaturize such optical systems. Since many applications rely on interferometric measurements, small linewidths are inevitable and gratings have to be integrated into the diode laser cavities. It has been shown before that high-order surface gratings etched into the ridge waveguides (RW) can be utilized for distributed Bragg reflectors (DBR). Recently, a diode laser array containing a set of individually controllable DBR-RWs around 905 nm was fabricated and characterized. Third-order surface gratings were applied to obtain stable wavelengths emission with small linewidths.

Fig. 1 shows the fabricated diode laser array with a footprint of 3 x 3 mm^2. It incorporates 24 lasers, each with a 1 mm long active section and a 1 mm long DBR section. The pitch between adjacent emitters is 87 µm; the RWs have widths of 2.5 µm to obtain fundamental lateral mode operation. The area behind the gratings serves as fan-out for the p-metal contacts. Bond pads are positioned at the rear end of the device and allow controlling the pump currents of each laser. The 2 µm long and 150 nm wide grating slits were defined with E-beam lithography. Gratings with periods $\Lambda_{D\#}$ were written, ranging from Λ_{D24} = 406.3 nm (diode D24) to Λ_{D01} = 412.2 nm (diode D01). We took the dispersion of the effective index into account to adjust the intended wavelengths spacing of 0.5 nm between adjacent emitters. The difference of the grating periods between them increases gradually, starting from $\Lambda_{D24} - \Lambda_{D23}$ = 0.25 nm to 0.26 nm. After E-beam lithography we applied an etching process to obtain V-shaped grating groves tapered towards the active region. Subsequent to grating implementation, a standard diode laser fabrication process followed. A front facet power reflectivity of 0.6 was adjusted to obtain small linewidth operation and high endurance against optical feedback. The DBR-RW laser array was then mounted p-side up on a C-mount (Fig. 2) for characterization.

Measurements of the array show threshold currents below 16 mA for all DBR-RW lasers. At a current of 40 mA, all 24 diodes emit with an optical output power > 17 mW. Fig. 3 summarizes optical spectra from the fabricated DBR-RW array. All spectra show single-mode emission with a side-mode suppression ratio > 50 dB. The peak wavelengths decrease linearly with rising emitter number. The spacing between adjacent emitters is close to 0.5 nm, as intended. However, the spectral distances reveal variations ranging from 0.41 nm to 0.56 nm that are randomly distributed. The overall wavelength uncertainty is 0.15 nm, which is in good agreement with the doubled spacing of the longitudinal modes. With increasing pump currents the peak wavelengths rise mainly because of joule heating. The shift measures 0.003 nm/mA, and up to two mode jumps occur in the current range from 20 mA to 60 mA. The mode jumps indicate that the spacings of the longitudinal modes are 0.072 nm wide. Linewidth measurements were performed with a Fabry-Perot interferometer (Toptica FPI 100). The emission linewidths are below 5.7 MHz, which is the resolution limit of the applied interferometer. Due to the small size, high conversion efficiency, and high spectral purity we believe the array will be highly attractive for sophisticated optical systems like 3D scanners.

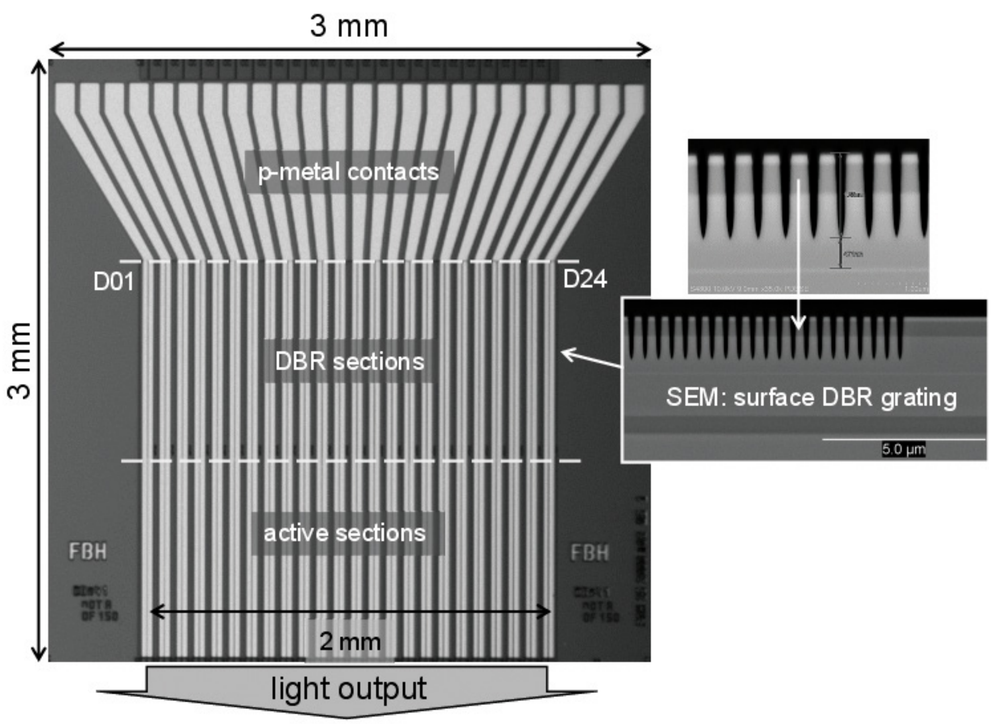


Fig. 1. AlGaAs-based diode laser array with 24 DBR-RW lasers.

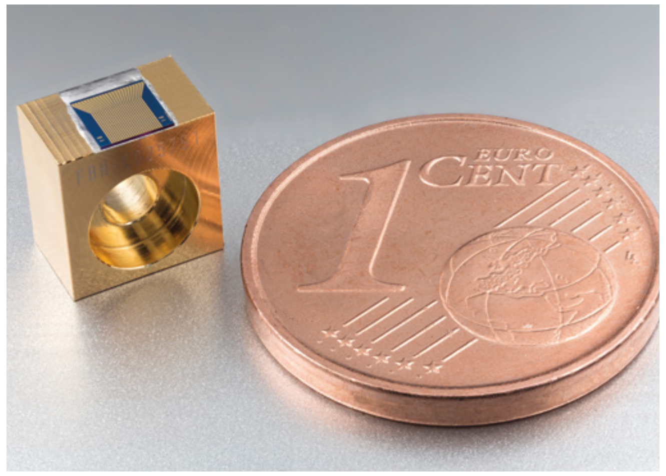


Fig. 2. Diode laser array on C-mount.

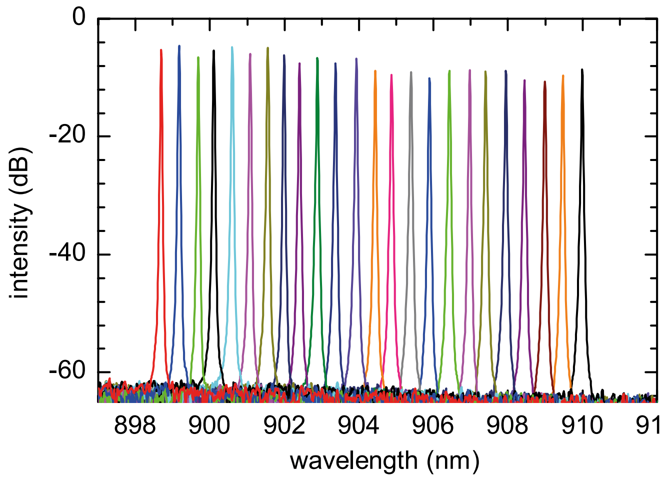


Fig. 3. Optical spectra of 24 single emitters on the array (current 40 mA).

Arrays aus Diodenlasern sind zentrale Komponenten, die sich ideal für optische Systeme zur präzisen Oberflächendetektion – etwa mit 3D-Scannern – eignen. Die Diodenlaser werden dabei mit definierten räumlichen Abständen auf einem Chip angeordnet. Dank ihrer geringen Abmessungen und hohen Konversionseffizienzen ermöglichen sie sogar die Miniaturisierung dieser Systeme. Da sie die Interferenz ausnutzen, müssen die einzelnen Laser neben einer genau definierten Emissionswellenlänge auch eine kleine spektrale Linienbreite besitzen. Das erfordert zusätzliche technologische Maßnahmen bei der Herstellung der Halbleiterlaser wie etwa das Einbringen von optischen Gittern in den Laserchip. Am FBH wurde ein 3 x 3 mm^2 großes, AlGaAs-basiertes Diodenlaser-Array entwickelt, auf dem 24 Laserchips mit Stegwellenleitern (engl. ridge waveguide; RW) platziert sind. Zur genauen Einstellung der Wellenlängen wurden in die Resonatoren Oberflächengitter eingebracht, die als Bragg-Reflektoren (engl. Distributed Bragg Reflector; DBR) wirken. Dabei sind die Gitterperioden so gewählt, dass der Abstand der Emissionswellenlängen benachbarter Chips 0,5 nm beträgt. Darüber hinaus verbessern die Oberflächengitter die spektralen Eigenschaften: Alle 24 Laserchips auf dem Array zeigen eine Seitenmodenunterdrückung > 50 dB bei Linienbreiten < 5,7 MHz.

Publications

O. Brox, J. Fricke, A. Klehr, A. Maaßdorf, M. Matalla, H. Wenzel, G. Erbert, "Array with 24 distributed Bragg reflector lasers for scanning applications: fabrication and characterisation" CLEO Europe, Jun. 21-25, Munich, Germany, ISBN: 978-1-4673-7475-0, paper CB_11_5(2015).

O. Brox, J. Fricke, A. Klehr, A. Maaßdorf, M. Matalla, H. Wenzel, G Erbert, "24-wavelength distributed Bragg reflector laser array with surface gratings", Electronics Letters 51 (17), 1352-1354 (2015).

Photonics Photonik

Impact of chirped quantum wells on the generation of optical picosecond pulses by monolithic colliding-pulse mode-locked lasers – enabling flexible sources for THz time-domain spectroscopy

The first laser device built in 1960 was capable of pulsed operation only, delivering a series of irregular spikes within the pulse duration. Since this discovery, much effort was made to generate ever shorter optical pulses with well-defined pulse shapes. Short infrared pulses in the lower and sub-picosecond range with high peak power and high repetition rates are greatly required for many applications including fiber communications, medical engineering, materials processing, and THz imaging as well as spectroscopy systems. In THz systems, short optical pulses are essential for a broad bandwidth. Very short pulses down to femtoseconds can be realized by expensive and bulky solid-state lasers. However, picosecond and sub-picosecond light pulses can be directly realized by semiconductor laser diodes, which are cost-efficient, have a small footprint, good conversion efficiency, and a high lifetime.

A well-established method to generate picosecond pulses with laser diodes is passive mode-locking, where a saturable absorber (SA) is placed into the cavity. Although gain and absorber sections are based on the same epitaxial layer structure, they are electrically separated and can thus be biased forward and reverse, respectively. The forward biased gain section serves as amplifying medium. The reverse biased SA creates a fixed phase correlation between the cavity modes located within the spectral width of the amplifying medium, resulting in the generation of short optical pulses.

Particularly short pulses can be obtained with colliding-pulse mode-locked (CPM) lasers, in which the saturable absorber is placed exactly in the center of the cavity surrounded by two gain sections. Counter propagating pulses jointly interact in the SA, thus sub-picosecond pulse widths are to be expected. Further pulse shortening could be achieved by broadening the spectral width of the amplifying medium. FBH constructed laser diodes with a double quantum well (DQW) as active layer, where the compositions x of the two $In_x Ga_{1-x}As_yP_{1-y}$ quantum wells differ by Δx so that the peak wavelengths of their gain spectra are detuned. Fig. 1 shows the surface of the mounted CPM laser with the tailored contact layout designed to achieve short pulse lengths.

To verify the influence of different QW compositions on the modal gain, subthreshold amplified spontaneous emission (ASE) spectra were measured and fitted on an analytical formula. Absorption spectra of the same DQWs were obtained from ASE spectra measured on devices with segmented (electrically separated) contacts. Fig. 2 shows modal gain and absorption spectra determined for several current densities and reverse voltages, respectively.

Increasing the current density j leads to a rise of the gain. If both QWs have the same composition (Δx = 0, see Fig. 2a) only one gain peak appears. In contrast, the chirped QWs (Δx = 0.08, see Fig. 2b) exhibit two gain peaks spectrally separated by ~ 30 nm, resulting in a broadening of the gain spectrum. The laser wavelengths (grey hatched areas in Fig. 2) are located on the long-wavelength gain slope. By increasing the reverse voltage U_{SA} from -0.6 V to -2.4 V the absorption coefficient becomes larger at the lasing wavelengths and above. The variation of the absorption in dependence on the absorber voltage is slightly reduced in case of the chirped QWs (Δx = 0.08).

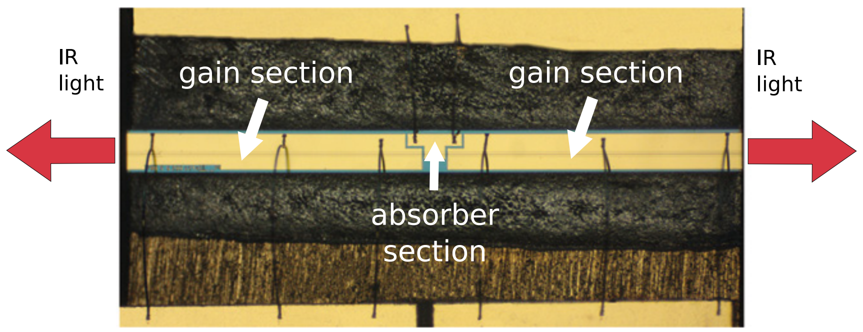


Fig. 1. CPM laser with 6 mm long cavity and 200 µm absorber section in the middle with bond wires and pads soldered on C-mount.

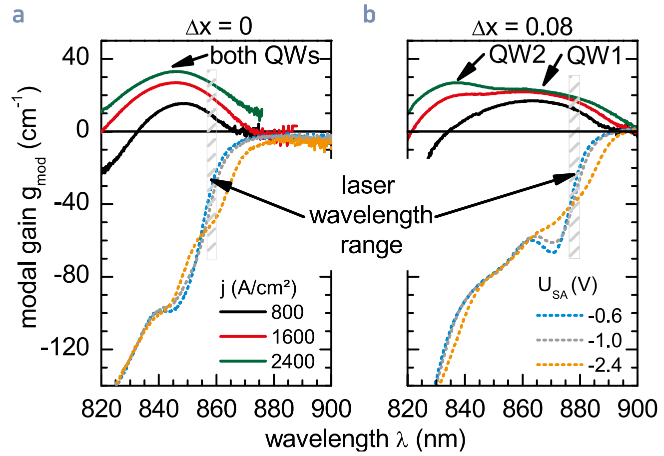


Fig. 2. Modal gain (solid curves) at variable current densities j and absorption spectra (dotted curves) at variable absorber voltages U_{SA} for different compositions of the two quantum wells (a) Δx = 0 and (b) Δx = 0.08.

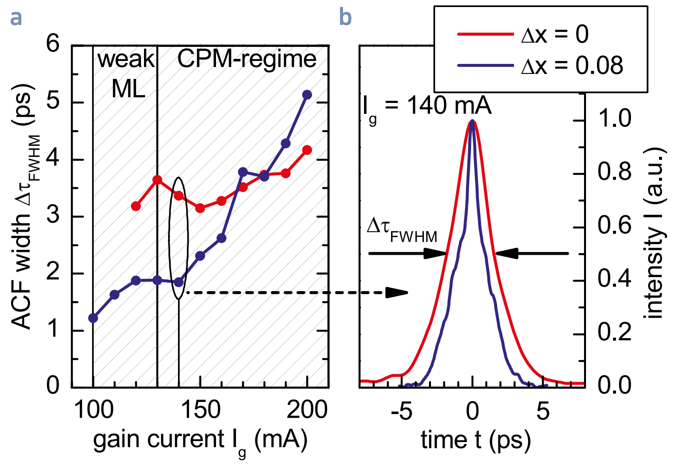


Fig. 3. Dynamical behavior of CPM lasers with different quantum well compositions at an absorber voltage of -1.0 V: (a) FWHM of autocorrelation functions (ACF) in dependence on gain current, (b) ACF traces.

The CPM lasers under study soldered on C-mounts are 6 mm long with back and front facet reflectivities of ~ 0.3. They feature an absorber length of L_{SA} = 200 µm, leading to a pulse repetition frequency of about 12.9 GHz. The lasers are operated at T = 20°C and U_{SA} = -1.0 V. Measurement results of the autocorrelation function (ACF) are shown in Fig. 3. The dependence of the full width at half maximum (FWHM) of the ACF on the current injected into the gain sections is depicted in Fig. 3a. Mode locking (ML) operation begins at 120 mA for Δx = 0 and 100 mA for Δx = 0.08. The shortest pulse widths are obtained just above threshold, and the pulse width increases with increasing gain current. Both lasers exhibit weak ML up to 130 mA. The gain currents for stable ML (CPM regime) range from 130 mA to 200 mA. Above 200 mA self-pulsating operation can be observed. The shortest pulses in the CPM regime are generated by the laser with chirped QWs (Δx = 0.08) and an ACF width of 1.9 ps at 140 mA. At same current, the ACF width of the pulses generated by the laser with equal QWs (Δx = 0) is 3.4 ps. Single traces of the ACF for this working point are shown in Fig. 3b. The experiment unveiled that the laser with broadened gain spectrum (Δx = 0.08) provides shorter pulses in the lower CPM regime as compared to the lasers without chirped gain (Δx = 0). The short widths of the pulses and the fact that the frequency can be varied by changing the gain current makes these lasers ideally suited for THz time-domain spectroscopy with asynchronous optical sampling technique.

These activities are supported by DFG (Deutsche Forschungsgemeinschaft) under contract KL 923/7-1.

Viele Kurzzeitanwendungen nutzen Pikosekundenpulse, die sich ideal mit Diodenlasern als sehr kompakte, leistungs- und kosteneffiziente Pulsquellen erzeugen lassen. Die Colliding-Pulse-Modenkopplung (CPM), bei der der Absorber in der Mitte der Kavität platziert ist, ist eine etablierte Methode, um ultrakurze Pulse zu generieren. Durch Verbreiterung des Gewinnspektrums des aktiven Mediums lassen sich die Pulse noch weiter verkürzen. Am FBH wurden 6 mm lange Doppelquantengraben-Diodenlaser (DQW) mit CPM-Layout und breitem Gewinnspektrum entwickelt. Die Komposition der beiden $In_xGa_{1-x}As_yP_{1-y}$-Quantengräben unterscheidet sich nicht (Δx = 0) oder um Δx = 0,08. Die Gewinnspektren des DQW mit Δx = 0,08 sind breiter als die des DQW mit Δx = 0. Die erreichten Pulsdauern betragen 1,9 ps (Δx = 0,08) und 3,4 ps (Δx = 0). Aufgrund der kurzen Pulse und der Möglichkeit, die Pulswiederholrate mittels Stromänderung abzustimmen, eignen sich diese Laser besonders gut für die Terahertz-Time-Domain-Spektroskopie.

Photonics Photonik

Capable short-pulse diode lasers – generating 1 nanosecond optical pulses with 7 watt power using ridge-waveguide lasers

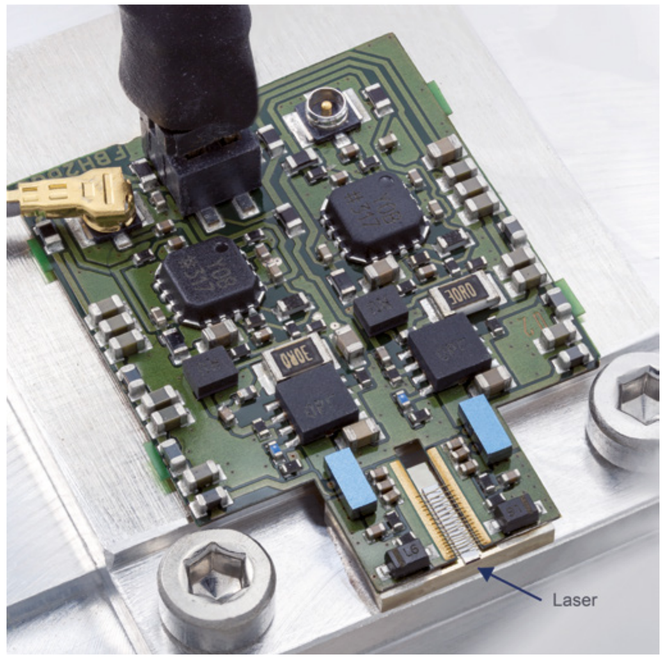


Fig. 1. High current ns laser driver with integrated ridge-waveguide laser diode.

There is an increasing demand for semiconductor-based sources which emit laser pulses in the nanosecond and pico-second ranges with peak powers from several watts to tens of watts. Lasers generating short optical pulses with widths in the range from 200 ps to 5 ns are key components for a broad range of applications including LiDAR (Light Detection and Ranging), e.g., for automotive systems (autonomous driving), 3D object detection, laser scanning (airborne, satellite, and terrestrial) as well as fluorescence spectroscopy and micro-machining systems. Flexible and easy-to-adjust laser sources covering the range of even shorter pulse durations from 100 ps to 1 ns are very interesting for special tasks such as seeding. In addition to the power and pulse width requirements, high repetition rates, good beam quality, and high efficiency are required.

Optical pulses can be generated with diode lasers by gain switching, Q-switching, and mode-locking. Gain switching, i.e., modulating the gain of the laser by turning on and off the current injected into the cavity, offers a simple, cost-effective, and power-efficient possibility to generate such pulses. However, pulse durations below 1 ns are typically hard to achieve because of the formation of a relaxation peak at the beginning of the pulse.

A new laser driver with a GaN transistor in the final stage has been developed at FBH. It generates current pulses up to an amplitude of 30 A with widths down to 0.5 ns. Pulse amplitude and width can be controlled separately. Very important for achieving high peak current, short pulse width, high repetition rate, and high power efficiency is the proper design of the output circuit. To reach short switching times at high pulse currents in the final stage, the mutual source inductance has been minimized. Fig. 1 shows the developed driver with integrated ridge-waveguide (RW) laser diode. The laser driver consists of two parallel circuits, which can be triggered separately (each 1 ns and 15 A) as well as together. In case of synchronous triggering, 1 ns current pulses with an amplitude of 30 V a pulse current of about 30 A can be reached.

The RW laser under study has an emission wavelength of about 670 nm and was grown on n-type GaAs via low-pressure metal-organic vapor phase epitaxy (MOVPE). The active region

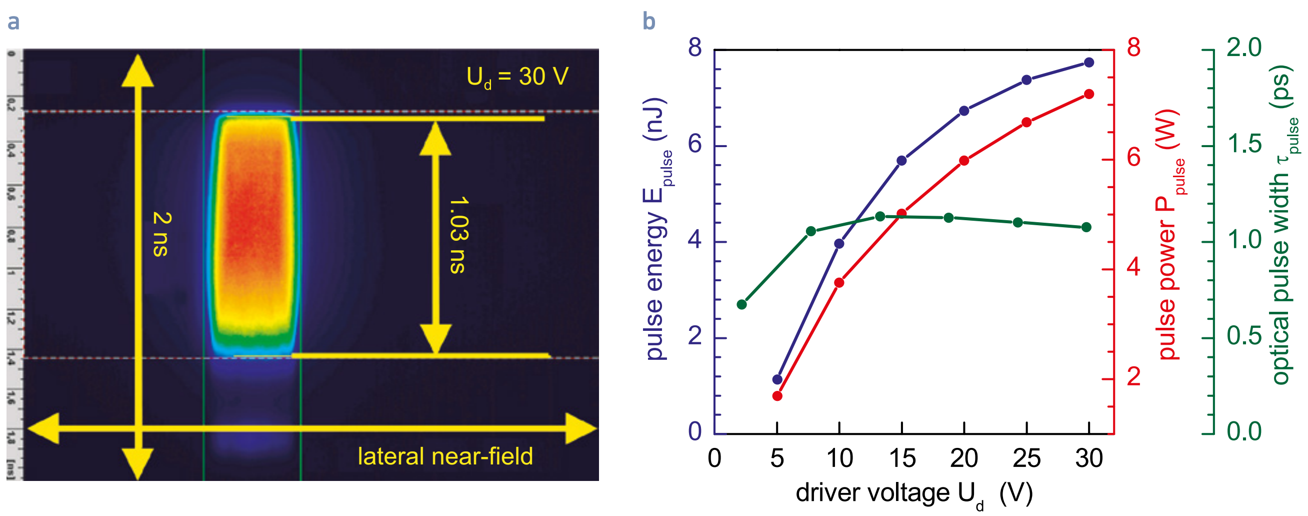


Fig. 2. Streak camera measurement (a) of the near-field intensity at a driver voltage of 30 V, (b) optical pulse power (red), optical pulse width (green), pulse energy (blue) vs. driver voltage.

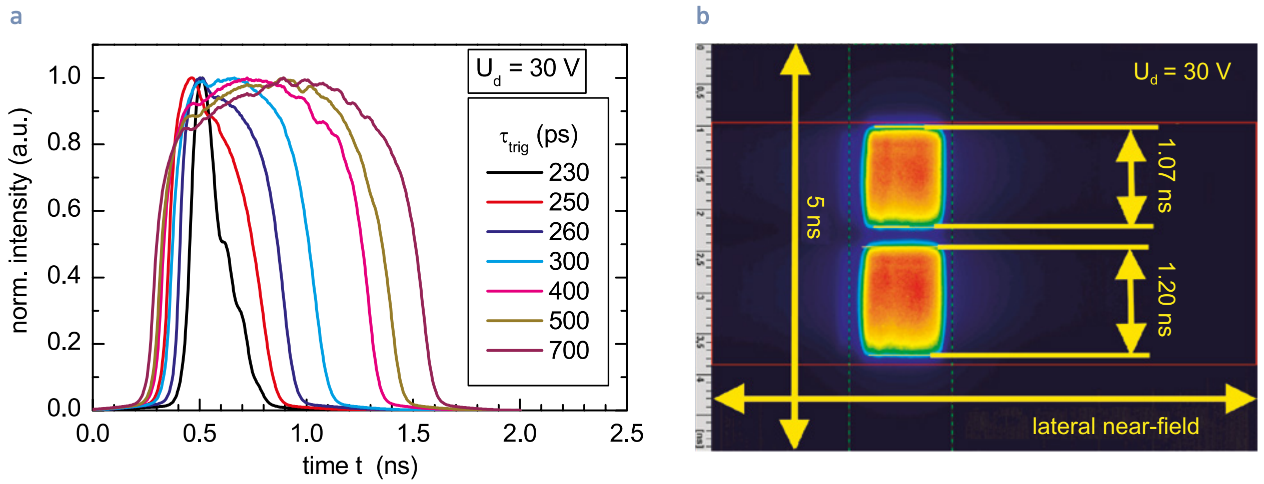


Fig. 3. Temporal behavior of the optical pulses for different trigger pulse widths between 230 ps and 700 ps (a) and streak camera measurements (b) of the near-field intensity of the optical pulses with a delay of 120 ps.

consists of a GaInP double quantum well (DQW). The vertical far field angle is about 30° full width at half maximum (FWHM). The laser with a cavity length of 3 mm and a ridge width of 15 µm was soldered p-side down on an AlN submount, which was mounted on an Al-plate. To minimize the inductance for pulse applications a large number of bond wires were used.

Fig. 2a shows the temporal behavior of the near-field intensity of an optical pulse measured with a streak camera. The driver voltage was 30 V, corresponding to an amplitude of the current pulse of about 30 A. The length of the optical pulse is about 1 ns, and the rise and fall times (10 % - 90 %) are about 0.1 and 0.3 ns, respectively. The pulse shows a nearly rectangular shape without any intensity fluctuations in the near-field.

Fig. 2b shows the optical pulse power (red curve), the measured optical pulse width (green curve), and the measured pulse energy in dependence on the driver voltage. As can be seen, a maximum pulse power of 7.2 W was reached. Measurements with a joule meter revealed that a maximum pulse energy of about 7.7 nJ was reached, comparable with the power measurements. The optical pulse width increased from 670 ps to about 1 ns with increasing driver voltage.

The possibility of a variation of the optical pulse widths was investigated by changing the trigger pulse width. This feature is needed for several applications such as automotive safety devices, 3D imaging, laser tomography, seed lasers for material processing, time imaging, and spectroscopy. Fig. 3a shows the dependence of the temporal behavior of the optical pulses for different trigger pulse widths between 230 ps and 700 ps at a constant driver voltage of 30 V. It can be seen that the optical pulse width can be changed between 230 ps and 1000 ps. At 230 ps pulse duration, a power of about 1.5 W was measured. With increasing optical pulse width the pulse power rises up to 7.2 W at ~ 1 ns.

For applications like, for example, pump probe experiments, a short time delay between the pulses is of interest. Fig. 3b shows streak camera measurements with a delay of about 1 ns between the two channels. Clearly, two closely spaced optical pulses are observed with a pulse distance of only 150 ps.

Publications

A. Klehr, T. Prziwarka, A. Liero, Th. Hoffmann, T. N. Vu, O. Brox, J. Fricke, F. Bugge, P. Ressel, A. Ginolas, H. Wenzel, H.-J. Wünsche, S. Schwertfeger, G. Erbert, G. Tränkle, "High power picosecond and nanosecond diode laser sources in the wavelength range 650 nm to 1100 nm", Proc. of 2015 High Power Diode Lasers and Systems Conference (HPD) and Photonex 2015, Coventry, UK, Oct.14-15, ISBN 978-1-4673-9177-1, pp. 3-4 (2015).

A. Klehr, T. Prziwarka, A. Liero, T. Hoffmann, H.-J. Wünsche, H. Wenzel, G. Erbert, "Nano-second high-current pulsed operation of ridge-waveguide lasers", Conf. on Lasers and Electro-Optics/Europe and European Quantum Electronics Conf. (CLEO/Europe-EQEC 2015), Jun. 21-25, Munich, Germany, ISBN: 978-1-4673-7475-0, cb-p.19-mon (2015).

Anwendungen wie etwa LIDAR-Systeme, 3D-Erkennung, Metrologie, Medizin, Spektroskopie und Seed-Systeme für die Materialbearbeitung benötigen leistungsfähige Kurzpuls-Diodenlasersysteme. Derartige Systeme erfordern Laserpulse von 100 ps bis zu einigen ns mit Leistungen bis in den Watt-Bereich, einstellbarer Folgefrequenz und guter Strahlqualität. Für diese Anforderungen müssen die Laser mit kurzen elektrischen Impulsen hoher Amplitude angesteuert werden. Dazu wurde im FBH eine Hochleistungselektronik mit GaN-Transistoren in der Treiberendstufe entwickelt, mit der Pulsströme bis 30 A und Pulsbreiten von 500 ps bis zu einigen ns erzeugt werden können. In diese Schaltung wurden Stegwellenleiterlaser integriert; damit ist es gelungen, Pulse von 7,2 W mit 1 ns Pulsbreite zu generieren. Ein Alleinstellungsmerkmal ist die kontinuierliche Variation der Pulsbreite von 230 ps bis 1,2 ns. Besonders hervorzuheben ist, dass sehr kurze Pulse mit hoher Leistung und geringem Pulsabstand erzeugt werden können, die für Pump-Probe-Experimente sehr geeignet sind.

Photonics Photonik

Pulsed laser source in the yellow spectral range for fluorescent lifetime spectroscopy

Optical spectroscopy has been restricted to watching the outside of living cells for a long time. However, probing the mobility of proteins or lipids and unraveling their interaction might enable new ways to develop specialized drugs for the treatment of diseases by inhibiting or enhancing molecular interactions. Using fluorescent labels represents one strategy to follow the targeted molecules with optical methods. Modern 'tagging' technologies allow attaching special self-fluorescent molecules or fluorophores onto selected proteins. Thus, when a living cell absorbs one or more discernable tagged proteins, their paths can be tracked within the cell by techniques like Fluorescence Lifetime Correlation Spectroscopy (FLCS) or Fluorescence Lifetime Microscopy (FLIM). The yellow and red spectral range is of particular interest, since fluorophores are more stable and the unlabeled cells show less auto-fluorescence compared to the blue spectral region. By applying pulsed lasers, one can not only use the spectral properties of the emitted fluorescence, but also its temporal properties which carry additional information and help discerning different stages of reactions within the cells.

The FBH is currently developing laser sources in the yellow wavelength range suitable for exciting fluorophores and measuring fluorescence spectra or, in pulsed operation, fluorescence decay time. These laser sources will be well suited for FLCS and other types of spectroscopic applications. As light emission from direct semiconductors in this wavelength range is not yet readily available, the work focuses on second harmonic generation (SHG) from high-power laser diodes emitting near 1120 nm. For pulsed operation, distributed Bragg reflector ridge waveguide (DBR-RW) laser are used as infrared source. Fig. 1 shows the schematic structure of the DBR-RW laser. The DBR laser utilizes a surface grating, which has the major advantage of requiring only a single epitaxial growth step. The laser is driven directly by short current pulses (< 1 ns) that are injected into the gain section, the so-called gain switching. With this method, the pulse power can be controlled directly by the current pulse amplitude. Additionally, the laser can be triggered at arbitrary repetition frequencies with almost constant temporal and spectral properties, which is an important feature for fluorescence spectroscopy. The lasing wavelength, defined by the DBR grating, is almost independent of the injected driving current in pulsed operation. This can be seen in Fig. 2, depicting a constant output wavelength versus output power. It also demonstrates that the spectral width of about 100 pm does not change significantly with increasing output power, which is relevant for the efficiency of the subsequent SHG process.

The pulsed infrared radiation typically shows a full width at half maximum (FWHM) of about 60 ps to 100 ps and pulse power up to the watt range. Fig. 3a illustrates a pulse shape of the infrared radiation. It was recorded at a repetition frequency of 40 MHz and an average output power of 4.2 mW. With a width of 60 ps FWHM, the pulse power could be determined to be 1.8 W. For second harmonic generation the pulses are coupled into a ridge waveguide nonlinear crystal. Fig. 3b shows the temporal performance of the pulsed green-yellow radiation at 558 nm at an average output power of 1.5 mW. It can be seen that the pulse width as well as the intensity of the trailing pulses decreased due to the SHG process, which increases the energy content in the laser pulse. The pulse power of 0.7 W leads to an optical conversion efficiency of 39 %.

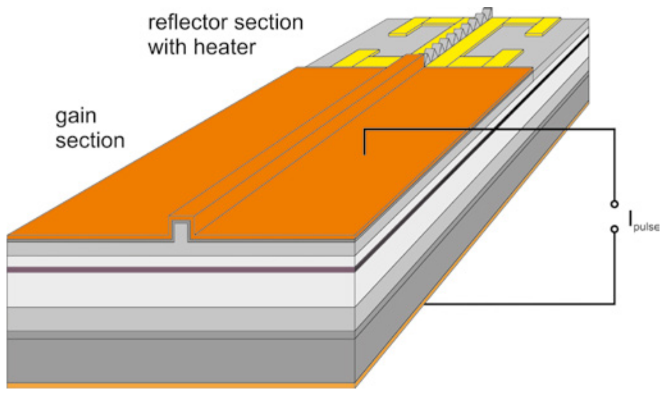


Fig. 1. Lateral and longitudinal structure of the DBR-RW laser. The gain section is driven with short current pulses. The resistive heater at the reflector section can be used for fine-tuning of the wavelength.

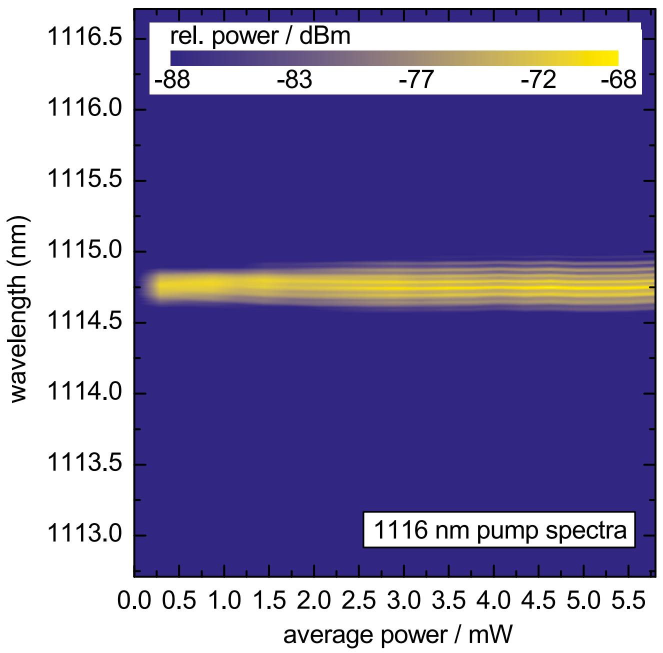
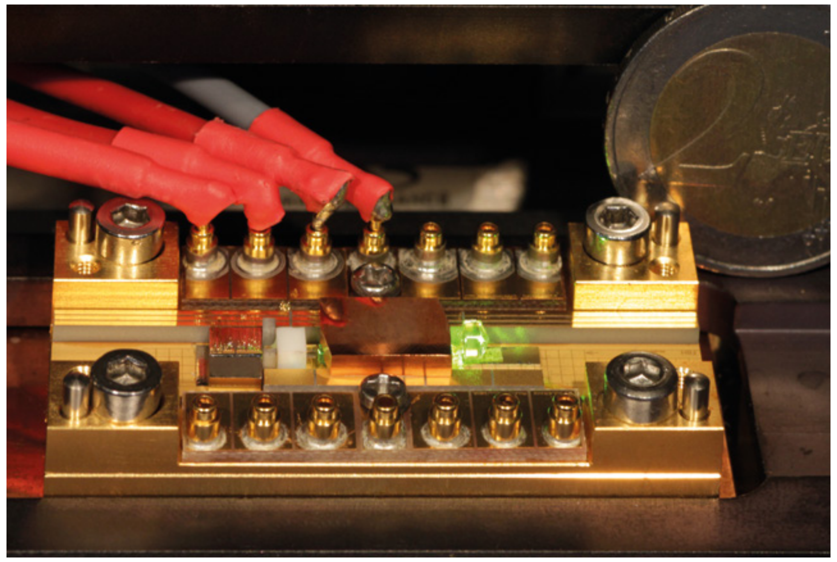


Fig. 2. Map of spectra of the infrared DBR-RW pump laser.



Demonstrator module with DBR-RW laser and SHG crystal emitting at 560 nm.

These properties, combined with a nearly diffraction limited beam, turn this 560 nm pulsed laser source into a very suitable laser device for fluorescent lifetime spectroscopy applications.

This work is supported within the InnoProfile Transfer initiative *YELLOW* by the Federal Ministry of Education and Research (BMBF) under contract 03IPT613Y.

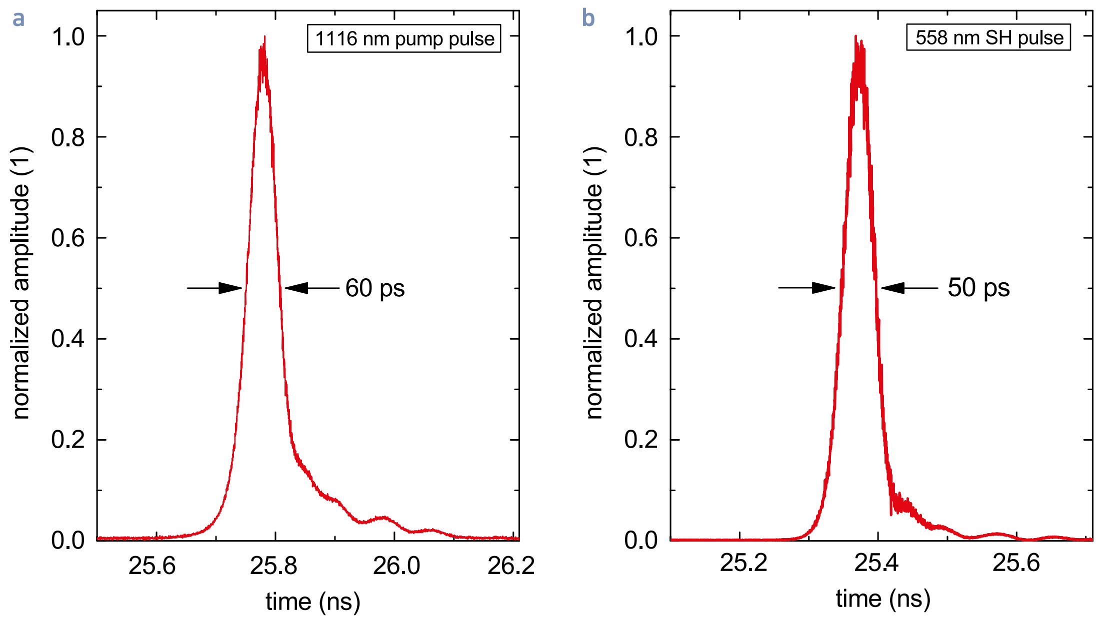


Fig. 3. Pulse shape of the 1116 nm pump (a) and the frequency doubled 558 nm radiation (b) measured at a repetition frequency of 40 MHz.

Publications

A. Kaltenbach, K. Paschke, F. Bugge, J. Fricke, K. Lauritsen, R. Erdmann, G. Tränkle, "Freely triggerable picosecond pulses from a DBR ridge waveguide diode laser near 1120 nm", Photonics Technology Letters, IEEE , vol.PP, no.99, pp.1-1, doi: 10.1109/LPT.2016.2517241 (2016).

F. Bugge, K. Paschke, G. Blume, D. Feise, U. Zeimer, M. Weyers, "Growth of laser diode structures with emission wavelength beyond 1100 nm for yellow-green emission by frequency conversion", J. Cryst. Growth 414, pp. 205-209 (2015).

A. Kaltenbach, R. Bege, K. Paschke, G. Tränkle, "Generation of 0.7 W second harmonic picosecond pulses near 560 nm using a DBR diode laser and a ridge-waveguide PPLN crystal," European Conference on Lasers and Electro-Optics - European Quantum Electronics Conference (OSA), paper CD_P_35 (2015).

Mittels Fluoreszenzspektroskopie lassen sich die Wechselwirkungen von lebenden Zellen beobachten. Die daraus gewonnenen Erkenntnisse helfen bei der Entwicklung von spezialisierten Arzneimitteln. Da Zellen im gelben Spektralbereich eine geringere Selbstfluoreszenz zeigen als im blauen, ist dieser für derartige Anwendungen besonders interessant. Das FBH entwickelt die zugehörigen Gelb emittierenden Laserquellen, die zusätzlich zum Dauerstrichbetrieb auch gepulst betrieben werden können. Damit lassen sich sowohl die spektralen als auch die zeitlichen Eigenschaften messen. Die optischen Pulse werden durch Gewinnschaltung von Distributed Bragg Reflector (DBR) Lasern bei Repetitionsfrequenzen bis 40 MHz erzeugt. Mit gepulsten DBR-Lasern, deren Strahlung in einem nichtlinearen Kristall verdoppelt wurde, konnte das FBH bereits Pulsleistungen von 0,7 W bei einer Emissionswellenlänge von 558 nm zeigen. Zusammen mit ihren stabilen spektralen Eigenschaften und einer nahezu beugungsbegrenzten Strahlqualität, M^2 < 1,3, sind diese gepulsten Laserquellen somit gut geeignet für die Anwendung in der Fluoreszenzspektroskopie.

Laser sources at 589 nm with up to the watt-level output power for medicine and bio-analytics

Several medical treatments in, for instance, dermatology or ophthalmology (eye surgery) base on laser light sources emitting in the yellow spectral range with an output power from the hundred milliwatt- to the watt-level. In this wavelength region, also many markers and molecules can be employed for biomedical analysis including flow cytometry, DNA sequencing, and refractometry. The latter application generally operates at the sodium D-lines at about 589 nm.

Users in the medical field, in industry, and research require efficient, durable, and portable laser sources. To meet these demands, semiconductor diode lasers are the most appropriate choice. However, direct emission from semiconductor laser sources is not available in the yellow spectral range with the necessary output power. Hence, frequency doubling of NIR laser light with a nonlinear crystal is commonly used. We realized a miniaturized module with a small footprint and high power efficiency comprising a diode laser, a nonlinear crystal, and beam forming optics (Fig. 1).

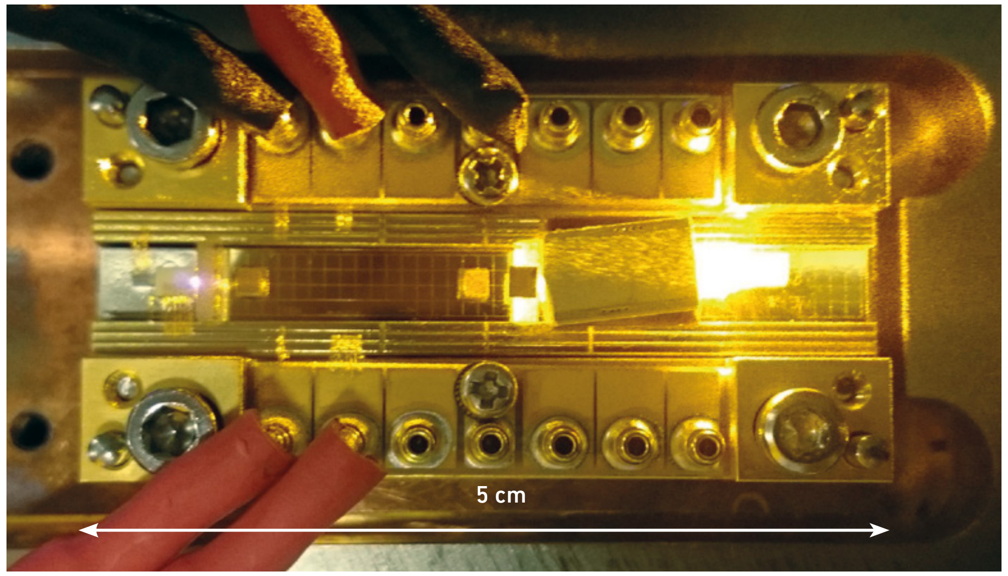


Fig. 1. Micro-module with a DBR-TPL and a RWG crystal emitting at 589 nm.

A diode laser structure was developed at the FBH that uses a highly strained defect-free InGaAs single quantum well. This structure was processed into DBR-tapered diode lasers (DBR-TPL), which consist of a ridge waveguide section with a DBR surface grating and a taper section to produce a high output power (upper inset in Fig. 2). The DBR-TPL exhibit single-mode operation (lower inset in Fig. 2) up to a taper current I_{TA} = 5 A at a temperature T = 25°C and a current through the ridge waveguide section I_{RW} = 200 mA. At this working point, a NIR output power close to 3 W near 1178 nm is reached (Fig. 3). A lifetime of more than 8,000 h for an output power of up to 1.25 W could be demonstrated. Hence, the lasers are suitable for long-term operation.

In a bench-top experiment such a DBR-TPL was used to investigate the properties of a nonlinear ridge waveguide (RWG) crystal. In order to reach high frequency doubled output powers at moderate pump powers, periodically poled magnesium-doped lithium niobate is used, which yields the highest nonlinearity. The power characteristics of the RWG crystal are shown in Fig. 3. Propagation loss through the optical setup limits the maximal available fundamental power (P_F) to 2.0 W at the working point. At this pump power, a frequency converted power (P_{SH}) of 0.86 W at 588 nm is achieved, which is almost double the previous world record published for RWG crystals. This corresponds to an optical-to-optical efficiency of 43 %.

The transmittance of the RWG crystal remains constant over the entire power range at 54 %, which can be deduced from the linear relationship between the power in front of (P_F) and behind the crystal (P_{SH}+P_{NIR}). This indicates the absence of any nonlinear absorption effect

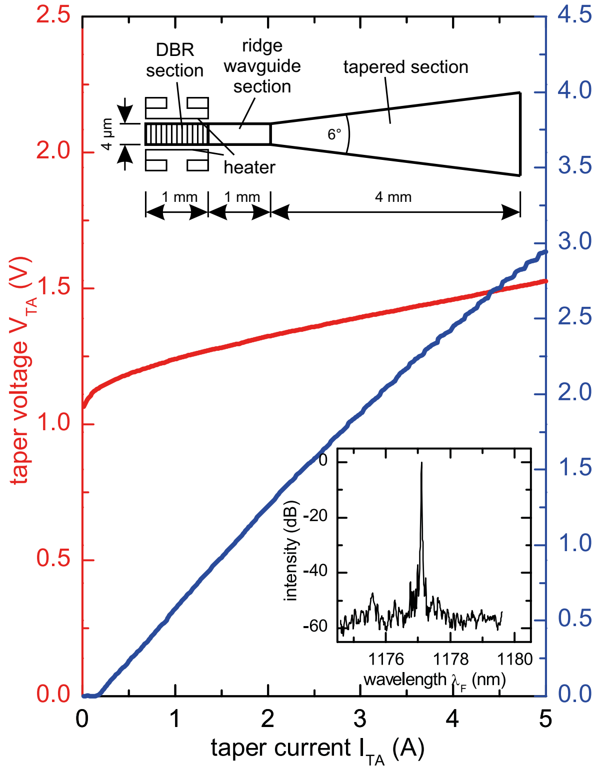


Fig. 2. Characteristics of a DBR-TPL: voltage-current (red) and power-current dependency (black). Upper inset: schematic of a DBR-TPL, lower inset: spectrum at a taper current of 5 A.

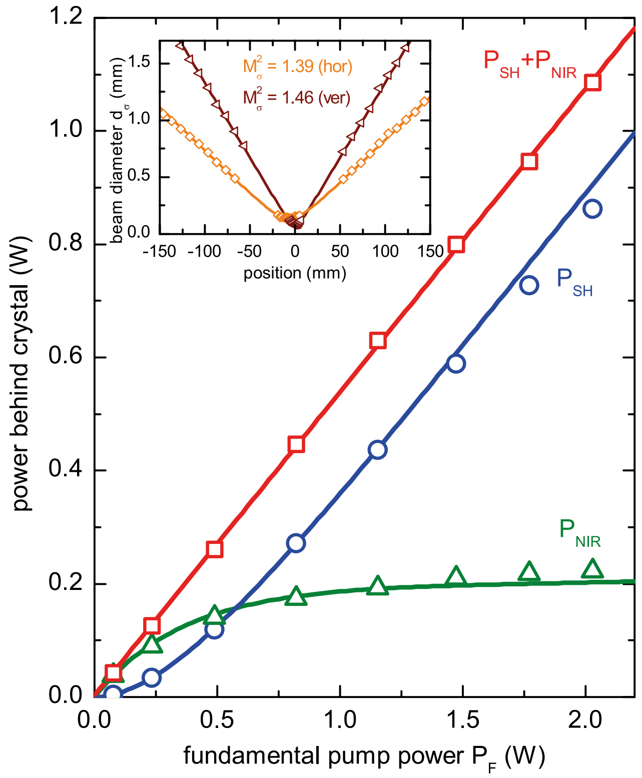


Fig. 3. Converted power P_{SH}, remaining fundamental power P_{NIR}, and the sum of both behind the crystal against fundamental pump power P_F. Inset: caustic of the generated beam.

usually encountered at such pump powers for wavelengths < 800 nm. Furthermore, the generated laser light is characterized by a nearly diffraction limited beam profile M_σ^2 < 1.5 (inset in Fig. 3).

Additionally, the DBR-TPL features a resistive heater close to the DBR grating (inset in Fig. 2), which enables wavelength tuning over more than 2 nm to meet the phase-matching condition of the crystal. Alternatively, the laser diode as well as the crystal can be tuned over more than 1 nm to address both sodium D-lines at 589.0 and 589.6 nm. First steps towards miniaturization have been undertaken on a micro-optical bench with a total length of 5 cm. The prototype generated an optical output power of more than 100 mW at 589 nm. This demonstrates the potential of the concept and is expected to lead to portable applications soon. If the power can be increased to the watt-level range, further applications such as guide star adaptive optics for environmental investigations, optical traps for sodium ion cooling, and LIDAR can be addressed.

We acknowledge the Federal Ministry of Education and Research (BMBF) for funding within the InnoProfile initiative "Unternehmen Region" (contract 03IPT613Y).

Basierend auf einem stark verspannten InGaAs-Quantenfilm konnten erstmalig DBR-Trapezlaser mit einer Emission bei 1178 nm hergestellt werden. Bei einer optischen Ausgangsleistung von über 1 W arbeiten diese mehr als 8.000 h zuverlässig (Fig. 2). Mithilfe eines nichtlinearen Rippenwellenleiterkristalls wird eine frequenzverdoppelte optische Leistung von 0,86 W bei einer Pumpleistung des DBR-Trapezlasers von 2,0 W erreicht (Fig. 3). Dies entspricht einer opto-optischen Umsetzung von 43 %. Zusätzlich lassen sich Laser und Kristall über 1 nm durchstimmen, sodass beide Natrium-D-Linien angesprochen werden. Damit steht eine Laserquelle für biomedizinische Anwendungen, von der Therapie bis hin zu Diagnose und Analyse, zur Verfügung. Sie eignet sich für weitere Bereiche wie etwa die Laserkühlung von Natriumionen. DBR-TPL und Kristall werden derzeit in portable Mikromodule integriert (Fig. 1), die sich durch ihre Kompaktheit und Energieeffizienz auszeichnen.

Publications

R. Bege, D. Jedrzejczyk, G. Blume, J. Hofmann, D. Feise, K. Paschke, G. Tränkle, "Watt-level second harmonic generation at 589 nm with a PPMgO:LN ridge waveguide crystal pumped by a DBR tapered diode laser", Opt. Lett., vol. 41, no. 7 (2016).

K. Paschke, G. Blume, O. Brox, F. Bugge, J. Fricke, D. Feise, J. Hofmann, H. Wenzel, G. Erbert, "Watt-level continuous-wave diode lasers at 1180 nm with high spectral brightness", Proc. SPIE 9348, 93480X (2015).

K. Paschke, F. Bugge, G. Blume, D. Feise, G. Erbert, "High-power diode lasers at 1178 nm with high beam quality and narrow spectra", Opt. Lett., vol. 40, no. 1 (2015).

F. Bugge, K. Paschke, G. Blume, D. Feise, U. Zeimer, M. Weyers, "Growth of laser diode structures with emission wavelength beyond 1100 nm for yellow-green emission by frequency conversion", J. Cryst. Growth 414, pp. 205 – 209 (2015).

K. Paschke, F. Bugge, G. Blume, D. Feise, W. John, S. Knigge, M. Matalla, H. Wenzel, G. Erbert, "Watt-level continuous-wave diode lasers at 1180 nm with InGaAs quantum wells", Proc. SPIE 8965, 896509 (2014).

Bringing SERDS out of the lab – compact handheld probe for real-world Raman investigations

Raman spectroscopy is a powerful and established tool to analyze organic and inorganic materials and substances. However, in situ applications bring along additional challenges. Fluorescence originating from, e.g., biological samples and ambient light such as daylight could mask the weak Raman signals and hence complicate identification, especially for unknown substances. Shifted excitation Raman difference spectroscopy (SERDS) is a capable and easy-to-use spectroscopic technique to overcome these drawbacks.

To achieve this, an excitation light source with two individually controllable emission lines with slightly shifted wavelengths is necessary. Samples are then successively excited with both laser lines. This way, the Raman signals are shifted by the amount of the spectral distance between both emission lines, whereas the background signals remain unchanged. After the measurement, the two measured Raman spectra are subtracted. The subtraction efficiently separates the Raman signals from background interferences and generates a SERDS spectrum. The FBH has already demonstrated suitable monolithic dual-wavelength diode lasers emitting at 785 nm and 671 nm, respectively.

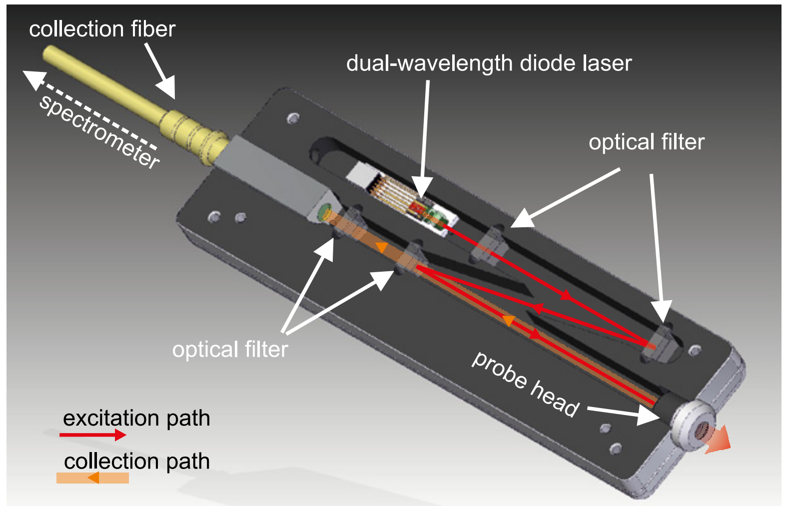


Fig. 1. Schematic inside-view of the SERDS probe.

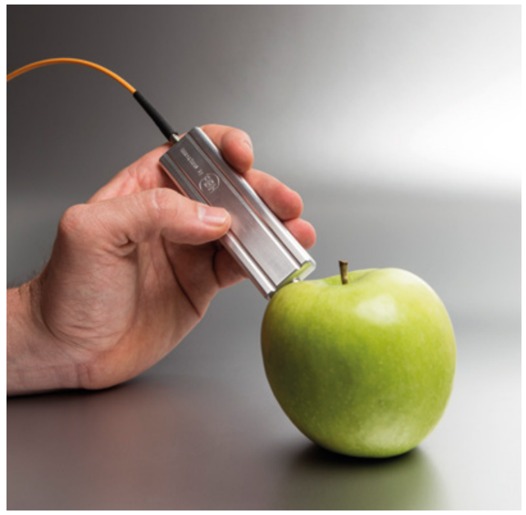


Fig. 2. Realized SERDS probe for in situ Raman investigations.

Now, the FBH has implemented such a 785 nm dual-wavelength diode laser into an in-house developed handheld probe. A schematic inside-view of the probe is presented in Fig. 1. The diode laser is mounted together with a thin-film thermoelectric module and a temperature sensor on an aluminum nitride micro-bench. Microoptics are used for beam collimation. This subassembly is implemented into the probe and realizes a compact open-beam configuration for the SERDS sensor. Optical filters such as a bandpass and long-pass edge filters are integrated into the probe to suppress the amplified spontaneous emission (ASE) of the diode laser and direct the beam to the probe head. Here, the laser light is focused via an aspheric lens to a sample. A quartz glass window protects the inner components. Based on the beam parameters of the excitation light source and optical simulations all microoptics are selected with respect to optimizing the collection efficiency for the generated Raman photons and reducing stray-light interference. The 180°-backscattered light is collected by the aspheric lens and is directed to the long-pass edge filters. Here, the laser light and the anti-Stokes shifted light are highly reflected. The Stokes shifted Raman photons pass the long-pass edge filters and are coupled via an achromatic lens into a multimode fiber (d_{core} = 105 µm), which is connected to a compact spectrometer. The handheld probe has a dimension of 100 mm x 28 mm x 12 mm. A realized device is shown in Fig. 2.

The diode laser provides an excitation power up to 120 mW at sample with a total power consumption of less than 0.6 W. Two separate controllable emission lines show a spectral width

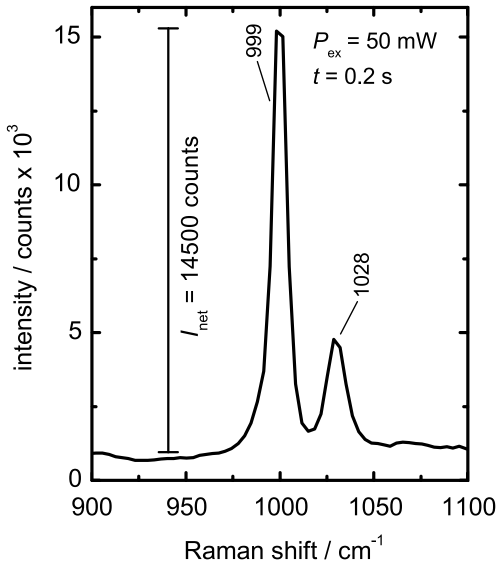


Fig. 3. Detailed view of a Raman spectrum of polystyrene measured with the SERDS probe at P_{ex} = 50 mW and 0.2 s integration time.

≤ 11 pm (≤ 0.2 cm^{-1}) and a spectral distance of 0.62 nm (10 cm^{-1}) over the whole power range, which is well suited for Raman spectroscopy and SERDS. Raman experiments were carried out using the SERDS probe and polystyrene (PS) as test sample. For these experiments, the excitation power was set to 50 mW, and a Raman spectrum was measured with 0.2 s integration time. A detailed view of such Raman spectrum is presented in Fig. 3, showing the strong Raman line of PS at 999 cm^{-1} with a net intensity of 14,500 counts. Here, a signal-to-background noise of S/σ_B = 580 and a signal-to-noise ratio of SNR = 115 – close to the shot noise limit – is achieved.

Beside this, stability tests were performed using 365 successively measured Raman spectra of PS with 0.2 s exposure time and a step size of 10 s. A stable center position of the Raman line at 999 cm^{-1} within a spectral window of 0.1 cm^{-1} is observed. The Raman intensity shows a peak-to-peak variation of less than ± 2%. Raman signals from the quartz glass window exhibit only minor interferences. The experimental results demonstrate the suitability of the handheld probe for Raman spectroscopy and enable in situ SERDS investigations for real-world applications.

Moreover, a portable SERDS system was realized and applied using this compact handheld probe with an implemented dual-wavelength diode laser emitting at 785 nm. SERDS field measurements were performed in an apple orchard using apples and green apple leafs as test samples. Here, SERDS efficiently separates the Raman signals from ambient daylight and fluorescence with an 11-fold improvement of the signal-to-background noise. The experimental results demonstrate the suitability of the handheld probe and the portable SERDS system for rapid in situ Raman investigations.

Parts of this work were realized within the project *DiLaRa* (Zwei-Wellenlängen-Diodenlasersystem für die Raman-Spektroskopie) supported by the Federal Ministry of Education and Research (BMBF) under contract 03V0207 and *USER-PA* (USability of Environmentally sound and Reliable techniques in Precision Agriculture) supported by the Federal Office for Agriculture and Food under contract FKZ 2812ERA039.

Publications

M. Maiwald, A. Müller, B. Sumpf, G. Tränkle, "A portable shifted excitation Raman difference spectroscopy system: device and field demonstration", J. Raman Spectrosc., published online, DOI: 10.1002/jrs.4953 (2016).

B. Sumpf, M. Maiwald, A. Müller, J. Fricke, P. Ressel, F. Bugge, G. Erbert, G. Tränkle, "Comparison of two concepts for dual-wavelength DBR ridge waveguide diode lasers at 785 nm suitable for shifted excitation Raman difference spectroscopy", Appl. Phys. B, vol. 120, no. 2, pp. 261-269 (2015).

M. Maiwald, B. Eppich, A. Ginolas, B. Sumpf, G. Erbert, G. Tränkle, "Compact handheld probe for shifted excitation Raman difference spectroscopy with implemented dual-wavelength diode laser at 785 nanometers", Appl. Spectrosc., vol. 69, no. 10, pp. 1144-1151 (2015).

M. Maiwald, B. Eppich, J. Fricke, A. Ginolas, F. Bugge, B. Sumpf, G. Erbert, G. Tränkle, "Dual-wavelength Y-branch distributed Bragg reflector diode laser at 785 nanometers for shifted excitation Raman difference spectroscopy", Appl. Spectrosc., vol. 68, no. 8, pp. 838-843 (2014).

Die Raman-Spektroskopie ist eine etablierte und leistungsstarke spektroskopische Messtechnik. In-situ-Messungen werden außerhalb des Labors jedoch häufig von Fluoreszenz- und Umgebungslicht wie z.B. Tageslicht gestört. Jedoch ermöglicht die Shifted Excitation Raman Difference Spectroscopy (SERDS), Raman-Signale von Störsignalen effizient zu separieren. Als Anregungslichtquelle für SERDS hat das FBH Zwei-Wellenlängen-Diodenlaser u.a. mit einer Emissionswellenlänge von 785 nm realisiert. Diese monolithische Lichtquelle wurde nun in eine neuartige, am FBH entwickelte Optode mit kompakten Abmaßen (100 mm x 28 mm x 12 mm) implementiert. Die Wellenlängen-stabilisierte Emission kann bis zu einer Anregungsleistung von 120 mW ex Optode über den Injektionsstrom am Diodenlaser flexibel eingestellt werden. Raman-Messungen mit diesem Handgerät zeigen eine hohe Sammeleffizienz und Raman-Signale mit einem Signal-zu-Rausch-Verhältnis, das nur durch das Schrotrauschen begrenzt ist. Die Ergebnisse sind mit einem Raman-Labormesssystem vergleichbar und eröffnen so Vor-Ort-SERDS-Messungen in vielen praktischen Anwendungsfeldern.

Photonics Photonik

Improving the spectral performance of extended cavity diode lasers using laser chips with bent ridge waveguide for high-precision measurements

Narrow-linewidth, wavelength-stabilized semiconductor lasers are required in a variety of fields. These include coherent optical communication and coherent manipulation of atoms and molecules as required, for example, in optical atomic clocks and matter-wave interferometers. To reduce the frequency noise, semiconductor laser chips are typically used in an extended cavity configuration using an external frequency selective element, e.g., a Bragg grating for optical feedback. The optical linewidth of extended cavity diode lasers (ECDLs) usually is in the kHz range for the Lorentzian linewidth and a few 100 kHz for time scales of about 1 ms.

Spectral purity is one of the key performance parameters of ECDLs. Experiments as well as simulations show the possibility of the coexistence of multiple stable continuous-wave (cw) modes [1, 2]. The presence of strong side modes effectively broadens the optical linewidths of ECDLs and, as experiments show, also increases frequency noise of the main mode. Radziunas et al. [1] and Tronciu et al. [2] present different approaches to improve the stability of cw-laser operation, e.g., by reducing the air gap between the Bragg grating and the laser chip or reducing the reflectivity of the Bragg grating. Here, we present another approach to improve the side-mode suppression of ECDLs by using semiconductor laser chips with an advanced ridge waveguide (RW) structure.

Fig. 1. shows schematics of the investigated ECDLs. These use 2 mm long, double quantum well InGaAs/AlGaAs RW diode laser chips with a ridge width of 5 µm together with a volume holographic Bragg grating (VHBG) with a Bragg wavelength of 1064.125 nm. The RW diode laser chips differ with respect to the ridge waveguide geometry. One laser chip features a straight (Fig. 1a) and the other a bent ridge waveguide (Fig. 1b). Bending of the waveguide allows for a chip layout which features one facet at right angle to the waveguide while the other is at an angle to the normal of the chip facet. At the latter facet, the effective reflectivity (an unwanted source of back-reflections) of $R_R = 10^{-3} \dots 10^{-4}$ achievable with anti-reflective coating only is further reduced by several orders of magnitude [3]. This strongly suppresses parasitic Fabry-Pérot modes of the laser chip. The layout of the laser chip with bent ridge waveguide consists of a 1 mm long straight and a 1 mm long bent section. The reflectivity of the front facets corresponds to R_F = 30 %. In both cases, the ECDL resonator length is chosen to feature a free spectral range of approximately 4 GHz.

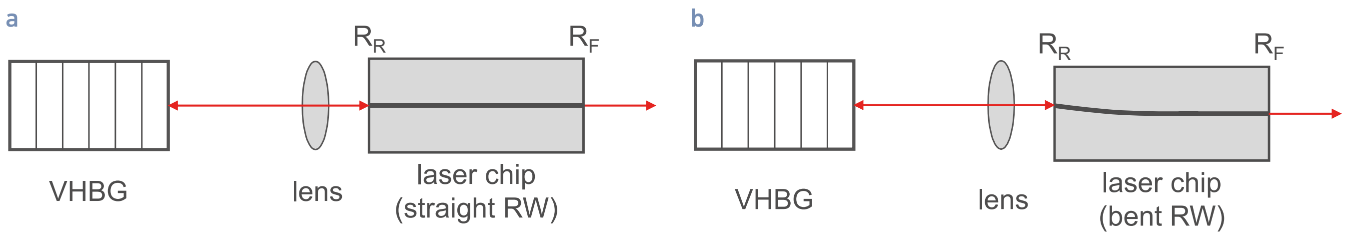


Fig. 1. Schematic of ECDL with (a) straight and (b) bent waveguide laser chip.

To measure the side-mode suppression ratio of the ECDLs, we carry out a heterodyne beat note measurement with a reference laser (a DFB laser in this case) to down-convert the optical spectrum of the ECDLs into the RF domain. The photodiode signal is recorded with an RF spectrum analyzer with a resolution bandwidth of 3 MHz. The side mode suppression ratio is calculated as the power ratio between the main peak and the respective side mode peak in the RF spectrum.

Fig. 2a shows the false color map of the RF spectra when tuning the injection current up from 30 mA (below threshold) for the ECDL, which is operated with the laser chip that features the straight ridge waveguide. The RF spectra are normalized to the RF peak power in the map. The corresponding side-mode suppression ratios of the respective +1st and -1st side modes are shown in Fig. 2b. At some current settings the side modes are only 3.3 dB below carrier. The

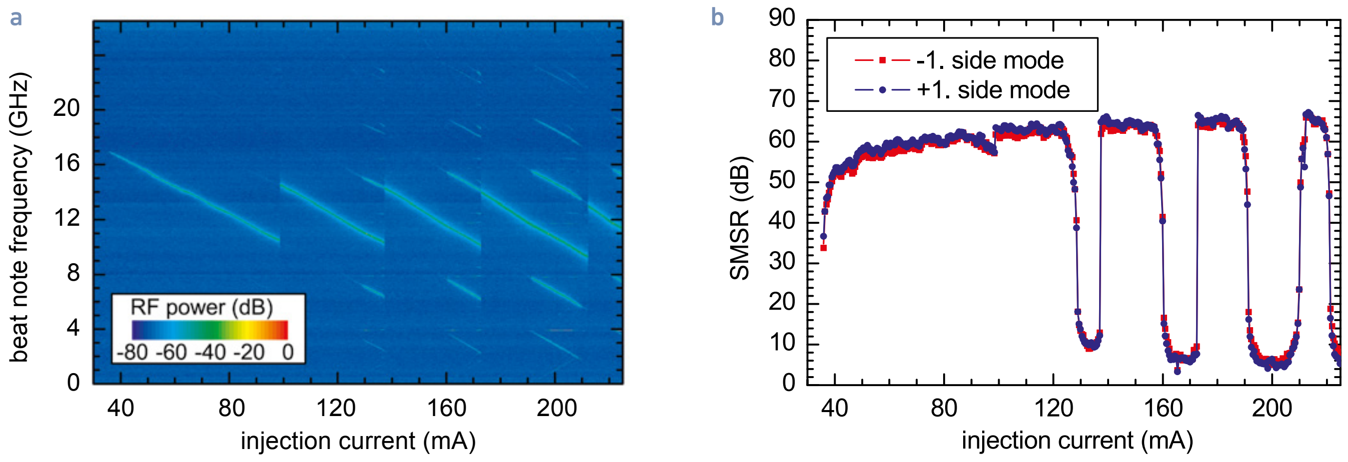


Fig.2. False color map of the RF spectra (a), and (b) the corresponding side-mode suppression ratios of the +1st and -1st side modes of the ECDL with straight waveguide laser chip.

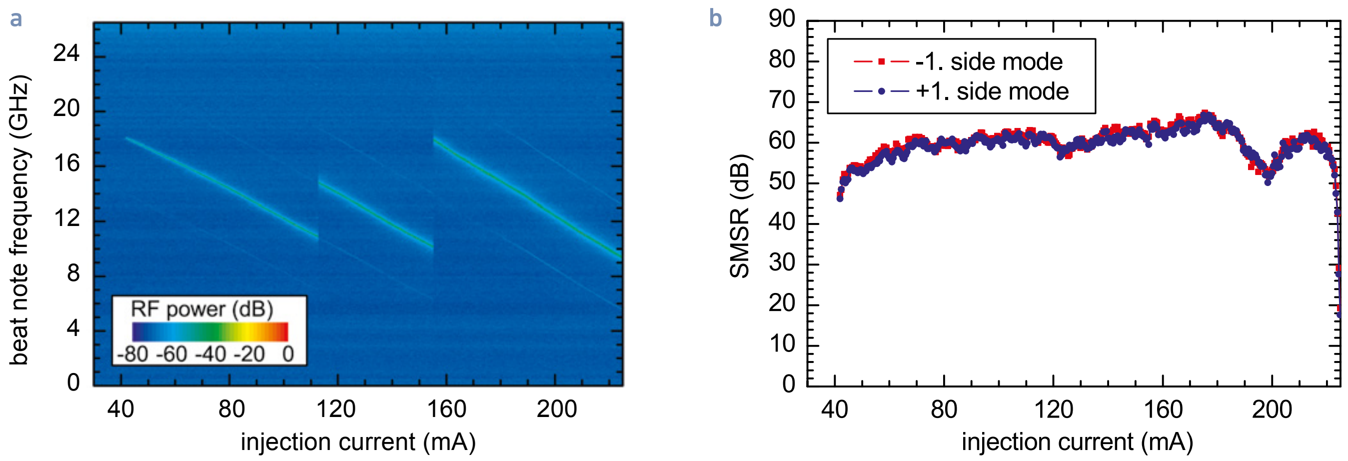


Fig. 3. False color map of the RF spectra (a), and (b) the corresponding side-mode suppression ratios of the +1st and -1st side modes of the ECDL with bent waveguide laser chip.

side modes appear periodically before a mode hop. After a mode hop the side mode suppression ratio exceeds 60 dB.

Fig. 3a and b show the false color map of the RF spectra and the side-mode suppression ratios of the ECDL operated with the laser chip that features the bent ridge waveguide. The minimum side mode suppression ratio between threshold and 220 mA corresponds to 46 dB. Compared to the ECDL with straight waveguide laser chip, the ECDL with the bent waveguide laser chip shows an increased side-mode suppression ratio, an increased single-mode tuning range and therefore features improved spectral stability and spectral purity.

This work is funded within the competitive procedure (SAW) of the Leibniz Association under grant number SAW-2013-FBH-3.

Publications

[1] M. Radziunas, V.Z. Tronciu, E. Luvsandamdin, C. Kürbis, A. Wicht, H. Wenzel, “Study of microintegrated external cavity diode lasers: simulations, analysis, and experiments”, IEEE J. Quantum Electron., vol. 51, no. 2, 2000408 (2015).

[2] V.Z. Tronciu, M. Radziunas, Ch. Kürbis, H. Wenzel, A. Wicht, “Numerical and experimental investigations of micro-integrated external cavity diode lasers”, Opt. Quant. Electron., vol. 47, no. 6, pp. 1459-1464 (2015).

[3] A. Klehr, H. Wenzel, J. Fricke, F. Bugge, G. Erbert, “Generation of spectrally stable continuous-wave emission and ns pulses with a peak power of 4 W using a distributed Bragg reflector laser and a ridge-waveguide power amplifier”, Opt. Express, vol. 22, no 20, pp. 23980-23989 (2014).

ECDLs (Extended Cavity Diodenlaser) werden aufgrund ihrer geringen optischen Linienbreite (full-width-at-half-maximum, FWHM) von einigen kHz für viele Anwendungen immer attraktiver. Dazu zählen u.a. die kohärente optische Kommunikation und die kohärente Manipulation von Atomen und Molekülen. Die spektrale Reinheit ist dabei einer der fundamentalen Parameter für die Performance der ECDLs. Sowohl experimentell als auch in Simulationen konnte das simultane Auftreten mehrerer stabiler Moden gezeigt werden [1, 2]. Sind die neben der Hauptmode auftretenden Seitenmoden stark genug, vergrößern sich dadurch effektiv die optische Linienbreite der ECDLs und das Frequenzrauschen der Hauptmode. Ein Ansatz, um die Seitenmodenunterdrückung bei ECDLs zu verbessern, ist der Einsatz von Diodenlaserchips mit gebogenem Rippenwellenleiter. Die +1-te und -1-te Seitenmode werden hierbei über einen großen Durchstimmbereich des Injektionsstromes mit mehr als 50 dB zur Hauptmode unterdrückt. Bei einem ECDL mit einem Diodenlaserchip mit geradem Rippenwellenleiter hingegen treten Seitenmoden auf, die weniger als 10 dB zur Hauptmode unterdrückt sind.

Understanding degradation processes in UV-B LEDs to enhance device lifetimes

(InAlGa)N-based ultraviolet (UV) light emitting diodes (LEDs) emitting in the UV-B spectral range between 280 nm and 320 nm have undergone rapid advances in the past years. Due to their meanwhile excellent performance characteristics, UV-B LEDs could replace traditional UV sources like mercury-discharge or excimer lamps in various applications. These include curing/hardening of specific polymer-based materials, various sensor applications, and even plant growth lighting. However, the lifetime of UV-B LEDs is still limited – from a few 1,000 h to about 10,000 h – and the physical degradation mechanisms are not yet fully understood. The lifetime of LEDs in general terms is often referred to as the reduction of the optical power of these devices, although the stability of other parameters such as peak wavelength and drive voltage is just as important. Currently, it is assumed that the crystalline perfection of the epitaxial layers, or more precisely, the concentration of point defects and extended defects mainly limit the lifetime of UV-B LEDs.

Within the Joint Lab GaN Optoelectronics, operated commonly by FBH and TU Berlin's Institute of Solid State Physics, UV-B LEDs emitting between 290 nm and 310 nm have been developed and investigated with respect to their lifetime and dominating degradation mechanisms. In the past year, the impact of the operating parameters (drive current, temperature in the active region) and the heterostructure design of the active region on the lifetime of LEDs were particularly studied. In general, we observed two different modes for the reduction of the optical power in our LEDs, which dominate at different times of operation (see Fig 1).

Mode 1 is represented by a fast drop of the optical power, which seems to level off within the first 100 h to 500 h [2]. The maximum reduction of the optical power during mode 1 ($\Delta P_{opt,1}$) of UV-B LEDs with a peak wavelength of 308 nm that are stressed at 100 mA and at different heatsink temperatures between 15°C to 80°C scales exponentially with the temperature. From an Arrhenius plot an activation energy of about 0.13 eV can be determined (compare Fig. 2a).

During mode 2 the optical power reduces much slower and shows a square-root time dependence, dominating at operation times beyond 100 h to 500 h. This points to a diffusion process to be involved in the degradation. The rate of the optical power reduction depends exponentially on the temperature which can be described by an activation energy of about 0.21 eV (compare Fig. 2b). Furthermore, the degradation rate for mode 2 scales with the current density.

In a second experiment, we compared the degradation of two types of UV-B LEDs with different heterostructure designs in and around the active region [1]. Their peak emission wavelengths are about 290 nm and 310 nm, respectively. The 290 nm LED has an Mg-doped AlN interlayer between the active region and the p-side, which cannot be found in the 310 nm LED. The function of this layer is to suppress electron leakage from the active region into the p-side of the LED and consequently to increase the radiative recombination in the active region [3]. Another difference can be found in the barrier between the p-doped layers and the topmost quantum well. The thickness of this layer is 2.5 nm in the 290 nm LED and 5.0 nm in the 310 nm LED. We have observed a much stronger reduction of the optical power emitted by the quantum well during mode 1 in the 290 nm LED than in the 310 nm LED (compare again Fig. 1). In contrast, the degradation rates during mode 2 are (-0.0058 ± 0.0024) $h^{-0.5}$ for the 290 nm LED and (-0.0073 ± 0.0006) $h^{-0.5}$ for the 310 nm LED and thus similar within the accuracy of the experiment. Therefore, it can be assumed that the impact of mode 1 may be reduced by an optimization of the LED pn-junction heterostructure design. On the other hand, mode 2 seems to be independent of the heterostructure design and is supposed to be mainly influenced by the types of crystalline defects and their distribution in the LEDs.

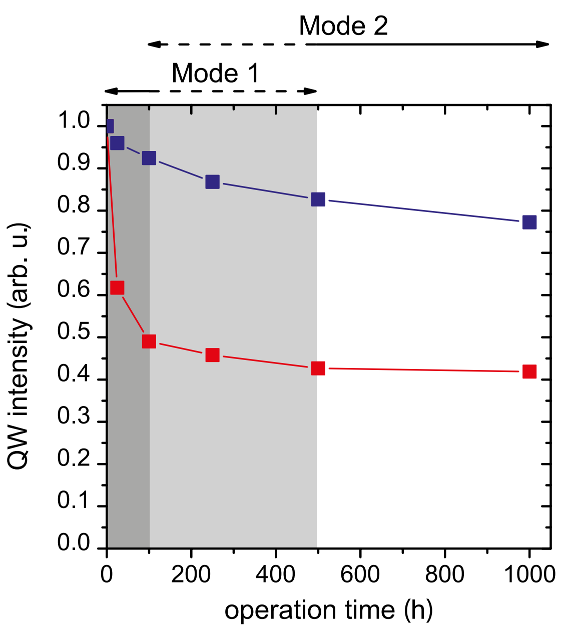


Fig. 1. Temporal evolution of the optical power of a 290 nm and 310 nm LED driven at a current of 100 mA and 20°C heatsink temperature (grey boxes = mode 1).

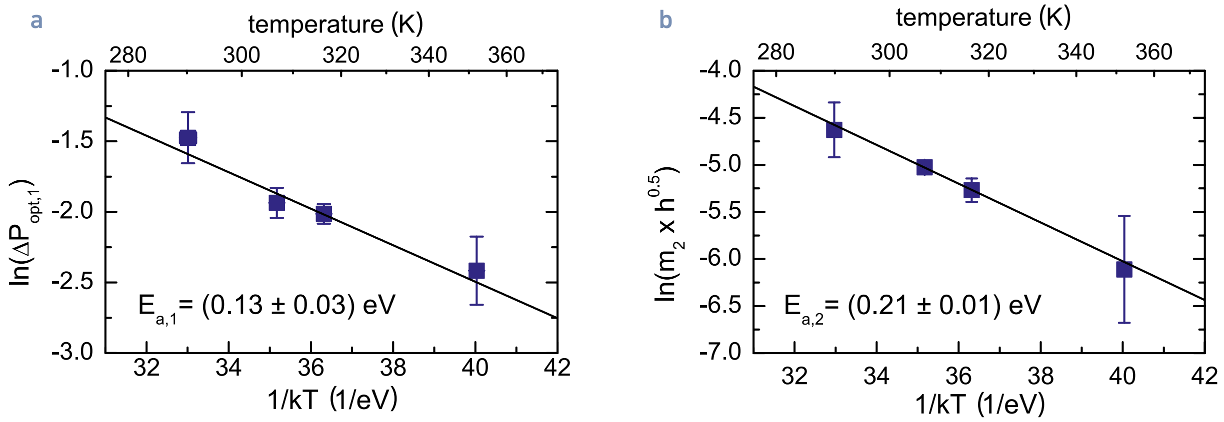


Fig.2. Temperature dependence of the degradation rates of 308 nm LEDs for (a) mode 1 (maximum power reduction = $\Delta P_{opt,1}$) and (b) mode 2 (degradation rate in $1/\sqrt{h} = m_2$) plotted in an Arrhenius plot to extract the activation energies of the degradation modes.

Currently, the lifetime of our 310 nm LEDs operated at 100 mA and room temperature is limited to 10,000 h (L50). The findings described above will be used to optimize the epitaxial layer structure und processing technologies to enhance the lifetime of our next-generation UV-B LEDs even further.

This work was partially supported by the Federal Ministry of Education and Research (BMBF) through the consortia project *Advanced UV for Life* under contracts 03ZZ0105A and 03ZZ0105B.

Dank der mittlerweile guten Leistungsparameter können UV-B-Leuchtdioden (280 – 320 nm) traditionelle UV-Quellen in verschiedenen Anwendungen ersetzen. Jedoch ist die Lebensdauer dieser LEDs noch auf einige 1.000 bis etwa 10.000 Stunden begrenzt, und die Degradationsmechanismen sind nicht vollständig verstanden. Alterung und Degradation von UV-B-LEDs wurden nun im Rahmen des Joint Lab GaN Optoelectronics eingehend untersucht. Es wurden zwei Modi der Abnahme der optischen Leistung gefunden, welche zu unterschiedlichen Betriebszeiten dominieren. Während der ersten 100 bis 500 Stunden (Modus 1) nimmt die optische Leistung schnell ab und die Abnahme skaliert mit der Temperatur. Dieser Degradationsmodus kann durch eine Anpassung des Heterostruktur-Designs um den pn-Übergang reduziert werden. Für längere Betriebszeiten (Modus 2) verläuft die Abnahme deutlich langsamer und zeigt eine Wurzelabhängigkeit von der Zeit. Dieser Effekt wird durch die Temperatur und die Stromdichte beeinflusst, jedoch nicht durch das Heterostruktur-Design. Aktuell werden die epitaktische Schichtstruktur und die Prozessierungstechnologien optimiert. Damit soll die Lebensdauer unserer UV-B-LEDs der nächsten Generationen weiter erhöht werden.

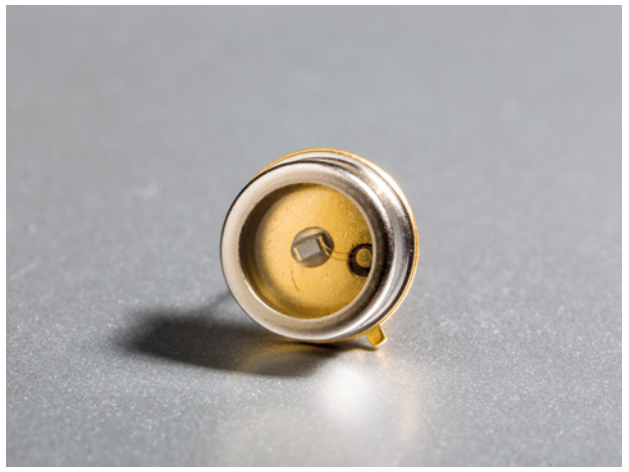
Publications

[1] J. Glaab, N. Lobo Ploch, J. Rass, T. Kolbe, T. Wernicke, F. Mehnke, Ch. Kuhn, J. Enslin, Ch. Stölmacker, V. Küller, A. Knauer, S. Einfeldt, M. Weyers, M. Kneissl, "Influence of the LED heterostructure on the degradation behavior of (InAlGa)N-based UV-B LEDs", Proc. of SPIE Vol. 9748, 974810-1 (2016).

[2] J. Glaab, Ch. Ploch, R. Kelz, Ch. Stölmacker, M. Lapeyrade, N. Lobo Ploch, J. Rass, T. Kolbe, S. Einfeldt, F. Mehnke, Ch. Kuhn, T. Wernicke, M. Weyers, M. Kneissl, "Degradation of (InAlGa)N-based UV-B light emitting diodes stressed by current and temperature", J. Appl. Phys. 118, 094504 (2015).

[3] T. Kolbe, F. Mehnke, M. Guttmann, C. Kuhn, J. Rass, T. Wernicke, M. Kneissl, "Improved injection efficiency in 290 nm light emitting diodes with Al(Ga)N electron blocking heterostructure", Appl. Phys. Lett. 103, 031109 (2013).

High injection efficiency of 265 nm UV-C LEDs for water disinfection



Encapsulated UV-C LED for water disinfection.

Many applications require narrow-band UV-C radiation in the wavelength range of 260 - 280 nm [1]. The commercially most promising ones are disinfection of water, air, and surfaces. Water disinfection systems currently apply almost exclusively low- and medium-pressure mercury lamps. Replacing these lamps with AlGaN-based UV-C LEDs is an attractive option as their emission peak can be exactly tuned by the semiconductor composition to 265 nm, the wavelength with the strongest germicidal effect. LEDs offer further advantages, since they are very compact, operate at low DC voltages, and do not emit strong heat. Additionally, they can be rapidly switched on and off and they can be dimmed. Therefore, they are ideally suited for water purification, especially for point-of-use application including airplanes, recreation vehicles, ships, and outdoor activities like camping.

The AlGaN UV-C LED technology has huge advantages in terms of spectral flexibility, compactness, and user friendliness. However, their power conversion efficiency and output power levels still lag behind those of mercury vapor lamps. A high density of crystal defects, originating from the AlN template, poor carrier injection efficiencies, and low light extraction efficiencies are the main limiting factors. The high defect density is typical for nitride-based heterostructures that are epitaxially grown on foreign substrates such as sapphire. This is due to lattice mismatch of the substrate and the epitaxially grown AlGaN layers leading to the formation of a high number of threading dislocations. These, in turn, reduce the probability for radiative recombination of charge carriers.

FBH and TU Berlin have recently started to develop UV-C LEDs emitting near 265 nm and demonstrated mW power level devices by carefully optimizing the entire LED fabrication chain. The defect density in the templates has been reduced by employing an epitaxial lateral overgrowth (ELO) process in which AlN was grown in a stripe geometry on patterned 2" AlN-sapphire substrates. Variations in the off-cut angle of the sapphire and the direction of the off-cut resulted in improved surface morphologies, reduced defect densities, and a change in the subsequent growth mode from step-bunching to step-flow [2].

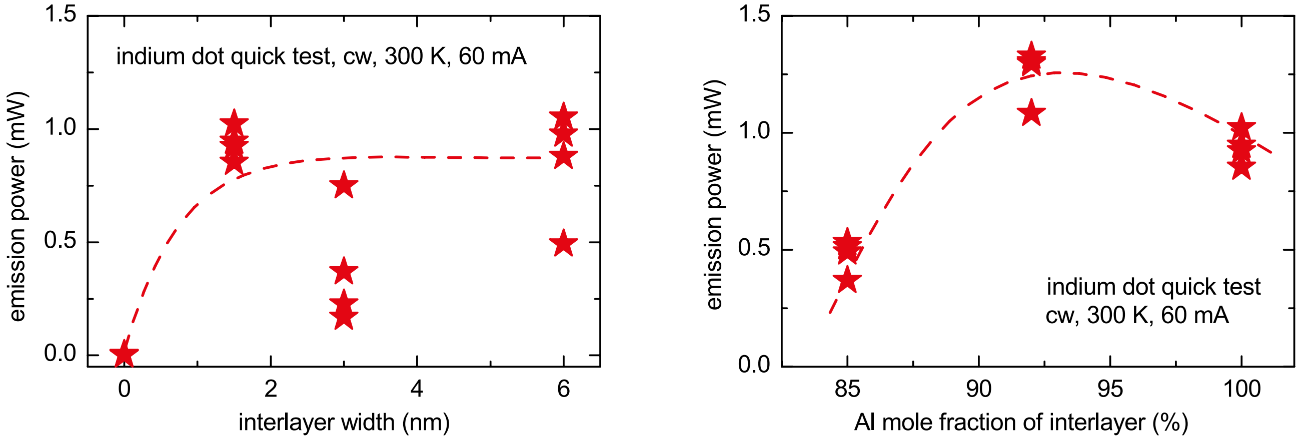


Fig.1. Output power from 265 nm LEDs measured on-wafer with varied thickness (left) and aluminum mole fraction of the $Al_xGa_{1-x}N$ interlayer (right).

The injection efficiency could be significantly improved by varying the heterostructure of the AlGaN electron blocking layer (EBL). An interlayer (IL) was inserted between the EBL, and the last barrier of the multi-quantum well (MQW) active region and its aluminum content and thickness were varied. On-wafer LED characterization in a quick test setup showed that LEDs without IL did not exhibit significant electroluminescence from the AlGaN MQW, while LEDs with a 1.5 nm thick AlN IL yielded approximately 1 mW output power at 60 mA injection current, as shown in Fig. 1. By optimizing the Al content of the AlGaN IL between 85 % and 100 %, a maximum emission power of 1.3 mW at 60 mA was found at 92 % Al content.

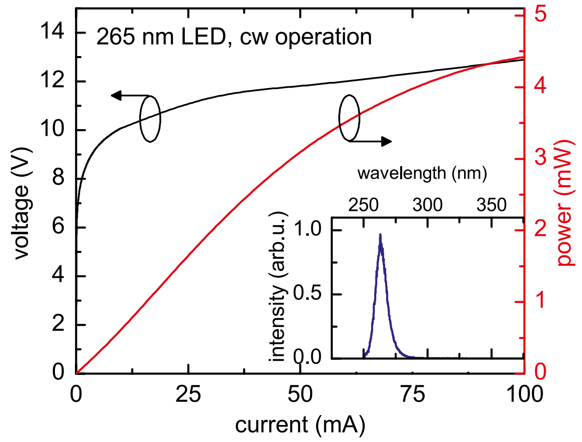


Fig.2. Output power-voltage-current characteristic and spectrum of a 265 nm LED flip-chip mounted on an AlN ceramic submount.

After optimizing this first generation of UV-C heterostructures, LED chips were fabricated from full 2-inch wafers. The front end process was based on our previous work on LEDs in the UV-B and deep UV-C range [5,6] and has now been adjusted for 265 nm LEDs. The respective single chips were diced from the wafer and flip-chip mounted on ceramic AlN submounts. The LED chips feature a single peak emission at 264 nm and 1.3 mW emission power at 20 mA injection current, as shown in Fig. 2. Cw output power exceeding 3 mW at 50 mA was demonstrated with an external quantum efficiency corresponding to 1.4 %. Despite the short development time, the performance level of this first generation of UV-C LEDs is already comparable to devices available on the market. A further increase in efficiency and output power is expected from future work, which will mostly focus on the electron injection process and improving light extraction from the LED chips.

This work was partially supported by the Federal Ministry of Education and Research (BMBF) through the consortia project *Advanced UV for Life* under contracts 03ZZ0106A and 03ZZ0106B.

Über die Zusammensetzung der Halbleiterschichten kann das Spektrum von UV-LEDs an die jeweilige Anwendung angepasst werden. Für die Wasserdesinfektion beispielsweise ist die Wellenlänge von 265 nm am effizientesten. FBH und TU Berlin haben nun begonnen, 265 nm UV-LEDs auf defektreduzierten, epitaktisch lateral überwachsenen (ELO) AlN-Saphir-Templates zu entwickeln. Mithilfe einer Zwischenschicht (IL) zwischen Elektronensperrschicht und Quantenfilm (QW) wurde die Injektionseffizienz der LEDs signifikant erhöht. Die auf dem Wafer gemessene QW-Lumineszenz stieg von fast null (kein IL) auf rund 1 mW bei 60 mA (1,5 nm dicker AlN-IL, Fig. 1). Durch Variation des IL-Aluminiumgehalts wurde eine maximale Emissionsleistung von 1,3 mW bei 92 % gefunden. Die zu LED-Chips prozessierten und in Flip-Chip-Geometrie montierten LEDs zeigten eine Ausgangsleistung von 1,3 mW bei 20 mA und mehr als 3 mW bei 50 mA (Fig. 2). Die externe Quantenausbeute lag bei rund 1,4 %. Die Werte dieser ersten Generation von UV-C-LEDs sind bereits vergleichbar mit denen von heute am Markt verfügbaren Bauelementen. Um die Effizienz und Ausgangsleistung weiter zu erhöhen, sollen im nächsten Schritt die Injektion der Elektronen in Quantenfilme und die Lichtextraktion weiter verbessert werden.

Publications

[1] M. Kneissl, J. Rass (Eds.), "III-Nitride Ultraviolet Emitters – Technology and Applications", Springer Series in Materials Science, ISBN 978-3-319-24098-5 (2016).

[2] A. Knauer, A. Mogilatenko, S. Hagedorn, J. Enslin, T. Wernicke, M. Kneissl, M. Weyers, "Correlation of sapphire off-cut and reduction of defect density in MOVPE grown AlN", phys. stat. sol. (b), vol. 253, no. 5, pp. 809-813 (2016).

[3] J. Rass, N. Lobo Ploch, "Nitride-based UV-LEDs and their application", Optik & Photonik, vol. 11, no. 3, pp. 36-40 (2016).

[4] A. Mogilatenko, A. Knauer, U. Zeimer, M. Weyers, "Defect distribution and compositional inhomogeneities in $Al_{0.5}Ga_{0.5}N$ layers grown on stepped surfaces", Semicond. Sci. Technol. 31(2), 025007 (2016).

[5] M. Lapeyrade, F. Eberspach, J. Glaab, N. Lobo Ploch, C. Reich, C. Kuhn, M. Guttmann, T. Wernicke, F. Mehnke, S. Einfeldt, A. Knauer, M. Weyers, M. Kneissl, "Current spreading in UV-C LEDs emitting at 235 nm", Proc. SPIE 9363, Photonics West, San Francisco, USA, Feb. 07-12, 93631P (2015).

[6] J. Rass, T. Kolbe, N. Lobo Ploch, T. Wernicke, F. Mehnke, C. Kuhn, J. Enslin, M. Guttmann, C. Reich, A. Mogilatenko, J. Glaab, C. Stölmacker, M. Lapeyrade, S. Einfeldt, M. Weyers, M. Kneissl, "High power UV-B LEDs with long lifetime", Proc. SPIE 9363, Photonics West, San Francisco, USA, Feb. 07-12, 93631K (2015).

[7] F. Mehnke, C. Kuhn, J. Stellmach, T. Kolbe, N. Lobo Ploch, J. Rass, M.-A. Rothe, C. Reich, N. Ledentsov Jr., M. Pristovsek, T. Wernicke, M. Kneissl, "Effect of heterostructure design on carrier injection and emission characteristics 295 nm light emitting diodes", Journal of Applied Physics 117, 195704 (2015).

[8] M. Kneissl, F. Mehnke, C. Kuhn, C. Reich, M. Guttmann, J. Enslin, T. Wernicke, A. Knauer, V. Küller, U. Zeimer, M. Lapeyrade, J. Rass, N. Lobo Ploch, T. Kolbe, J. Glaab, S. Einfeldt, M. Weyers, "Deep Ultraviolet LEDs: from materials research to real-world applications", IEEE Summer Topical Meeting Series (SUM), 9-10 (2015)

[9] U. Zeimer, J. Jeschke, A. Mogilatenko, A. Knauer, V. Küller, V. Hoffmann, Ch. Kuhn, T. Simoneit, M. Martens, T. Wernicke, M. Kneissl, M. Weyers, "Spatial inhomogeneities in structural and optical properties of $Al_xGa_{1-x}N$ quantum wells induced by surface morphology of AlN/sapphire templates", Semicond. Sci. Technol. 30 (11), 14008 (2015).

For further information:

http://www.fbh-berlin.com/research/photonics

III-V Electronics

III/V-Elektronik

III/V-Elektronik

Das übergreifende Ziel der Forschungsarbeiten des FBH im Bereich III/V-Elektronik ist, die Grenzen der elektronischen Bauteile hinsichtlich effizienter Leistungserzeugung bei hohen Frequenzen, hohen Spannungen und kurzen Schaltzeiten systematisch zu erweitern.
Das Spektrum reicht von schneller Leistungselektronik über die Mobilfunkfrequenzen im unteren GHz-Bereich bis hin zu Sub-Millimeterwellen. Alle Aktivitäten basieren auf der III/V-Halbleitertechnologie. Sie umfassen derzeit die folgenden Themen:

- ***HF-Leistungsmodule auf Basis von GaN für den Einsatz in Mobilfunk-Basisstationen*** – der Schwerpunkt liegt auf Konzepten zur Reduzierung der Verlustleistung (Supply Modulation) und zur Erhöhung der Frequenzagilität (BST-Varaktoren).

- ***Digitale Leistungsverstärker*** – das FBH entwickelt neue digitale Verstärkerarchitekturen für die drahtlose Infrastruktur, die Flexibilität mit Leistungseffizienz verbinden. Langfristiges Ziel ist der komplett digitale Transmitter.

- ***Terahertz-Komponenten & -Systeme*** – der Schwerpunkt liegt auf integrierten Schaltungen mit Indium-Phosphid (InP) Heterobipolartransistoren (HBTs), derzeit bis zum 250 GHz-Band. Dabei kommt ein Transfer-Substrat-Prozess zur Anwendung, der auch eine InP-auf-BiCMOS-Heterointegration auf Waferebene beinhaltet. Damit können kompakte integrierte Frontend-Module für Radar-, Sensor- und Kommunikationssysteme realisiert werden.

- ***Erkundung von plasmonischen Effekten für die Terahertz-Detektion und -Emission*** – diese Phänomene versprechen eine Einsatzmöglichkeit von Transistorstrukturen weit oberhalb der klassischen Grenzfrequenzen im 1 THz-Bereich. Wir nutzen dazu die GaN-Technologie.

- ***GaN-basierte Schalttransistoren & Schottkydioden für hohe Spannungen*** – für hocheffiziente Leistungs-Umrichter mit hoher Taktrate, geringem Gewicht und Volumen. Damit eignen sie sich für vielfältige Anwendungen, u.a. im Bereich Elektromobilität.

- ***Mikroplasmen & Lasertreiber*** – GaN-Transistoren werden auch dazu genutzt, um kompakte Mikroplasmaquellen, z.B. für die Aktivierung von Oberflächen, zu entwickeln sowie schnelle Hoch-Strom-Treiber, die mit Laserdioden aus dem FBH zu Pulsquellen integriert werden.

Neben der III/V-Halbleitertechnologie erfordern diese Forschungsarbeiten die entsprechende Expertise bei Simulation, Modellierung, Schaltungsdesign und Charakterisierung.

III-V Electronics

The overall target of FBH's research activities in the field of III-V electronics is to push the limits of electronic devices in terms of efficient power generation at high frequencies, high voltages, and short switching times. The frequency spectrum ranges from fast power electronics through the mobile communication bands in the lower GHz range to sub-millimeter waves. All activities are based on III-V semiconductor technology; they presently encompass the following major topics:

- ***Microwave power amplifiers based on GaN for the use in mobile base stations*** – the focus is on concepts reducing power losses (supply modulation) and enhancing frequency agility (BST varactors).

- ***Digital power amplifiers*** – the FBH develops novel digital amplifier architectures for the wireless infrastructure. Long-term target is the complete digital transmitter.

- ***Terahertz components & systems*** – the focus is on integrated circuits up to the 250 GHz band so far, using indium phosphide (InP) bipolar transistors (HBTs). A transferred-substrate process is applied including a wafer-scale InP-on-BiCMOS heterointegration option. With these circuits, compact integrated frontend-modules for radar, sensor and communication systems can be realized.

- ***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.

- ***GaN-based switching transistors & Schottky diodes for high voltages*** – for high-efficiency power converters with high clock speed, low weight, and volume. They are well-suited for a great variety of applications, e.g., in the field of electro mobility.

- ***Microplasmas & laser drivers*** – GaN transistors are also used to develop compact microplasma sources for, e.g., activation of surfaces and high-speed high-current drivers for laser diodes that are integrated into FBH pulse laser sources.

Besides the III-V semiconductor technologies, these research activities require the corresponding advanced simulation, modelling, circuit design, and measurement expertise.

Advances in class-G microwave power amplifiers for wireless communications

Microwave power amplifiers (PA) are critical components in the wireless infrastructure since they cause the main part of distortions and consume most of the power. In modern communication systems modulation schemes with high peak-to-average power ratio (PAPR), e.g., orthogonal frequency-division multiplexing (OFDM), are used to achieve high spectral efficiency. This is necessary to meet the growing demand for bandwidth in wireless communications. However, the very high peak-to-average power ratios of OFDM signals require a conventional PA to be operated in back-off condition most of the time to ensure linear amplification up to the peak power.

A common problem with linear PA technologies is the lack of back-off efficiency, i.e., the PA's efficiency will be low if not operated at maximum output power. A possible solution to increase the back-off efficiency is to reduce the supply voltage when operating the PA at lower output powers, which keeps the dissipated power losses low. In class-G supply modulation the supply voltage of the PA is adjusted in discrete levels, depending on the instantaneous envelope amplitude of the modulated RF signal. The power losses for a class-A PA without and with class-G modulation are illustrated in Fig. 1. In this example, the losses could be reduced by 60 % due to implementing a simple two-level class-G modulation. Accordingly, FBH has intensified its research on this type of PAs. The work comprises both high-efficiency GaN-based modulators for switching frequencies up to 100 MHz and the respective GaN PAs for long-term evolution (LTE) applications, tailored for class-G operation.

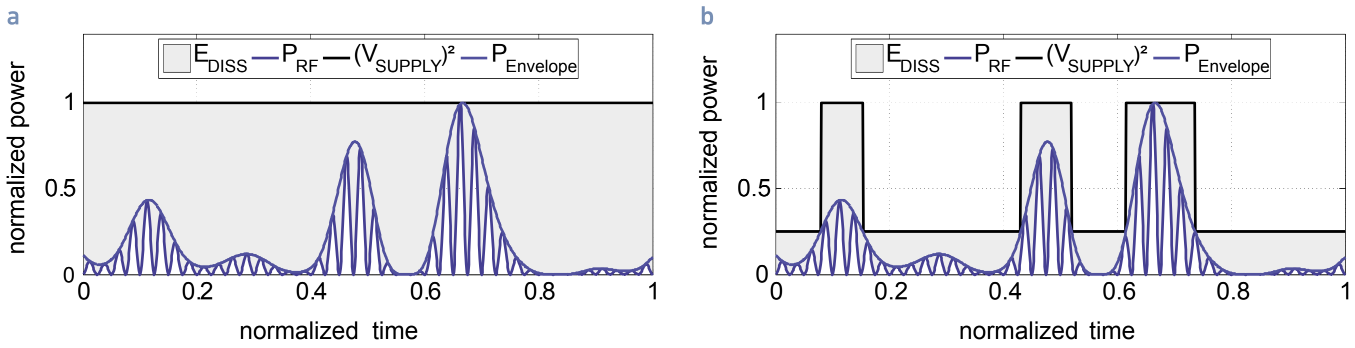


Fig. 1. Dissipated energy for (a) a conventional power amplifier with constant supply voltage, (b) a two-level class-G modulated power amplifier.

But, switching the supply voltage affects the gain and phase of the PA, which degrades the linearity of the PA. At the supply switching threshold there is a sharp discontinuity in gain and phase, which is shown in Fig. 2 for a three-level class-G system. Therefore, linearity enhancement techniques based on baseband digital predistortion (DPD) need to be employed to restore linear amplification. Since class-G modulation is a new topic for RF applications, DPD predistorter models optimized for class-G PA systems are not yet available. Commonly used DPD models have been tested on a two-level class-G modulated system, but have shown poor improvement due to the discontinuity of the gain and phase. Therefore, a novel DPD model which improves linearization of the switching transients has been developed.

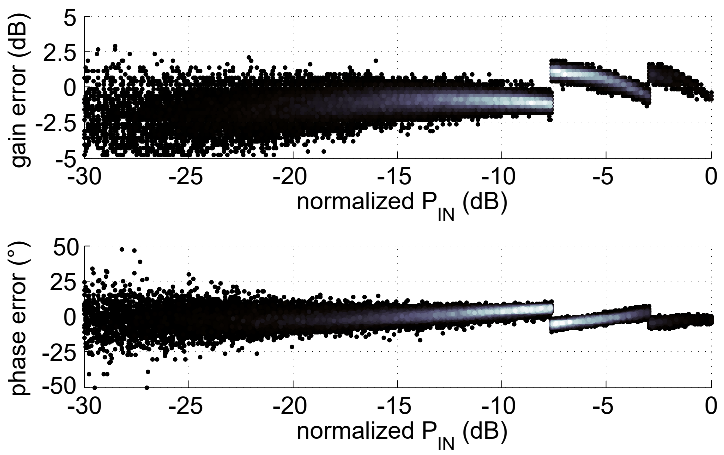


Fig. 2. Amplitude and phase distortion in a three-level class-G modulated power amplifier.

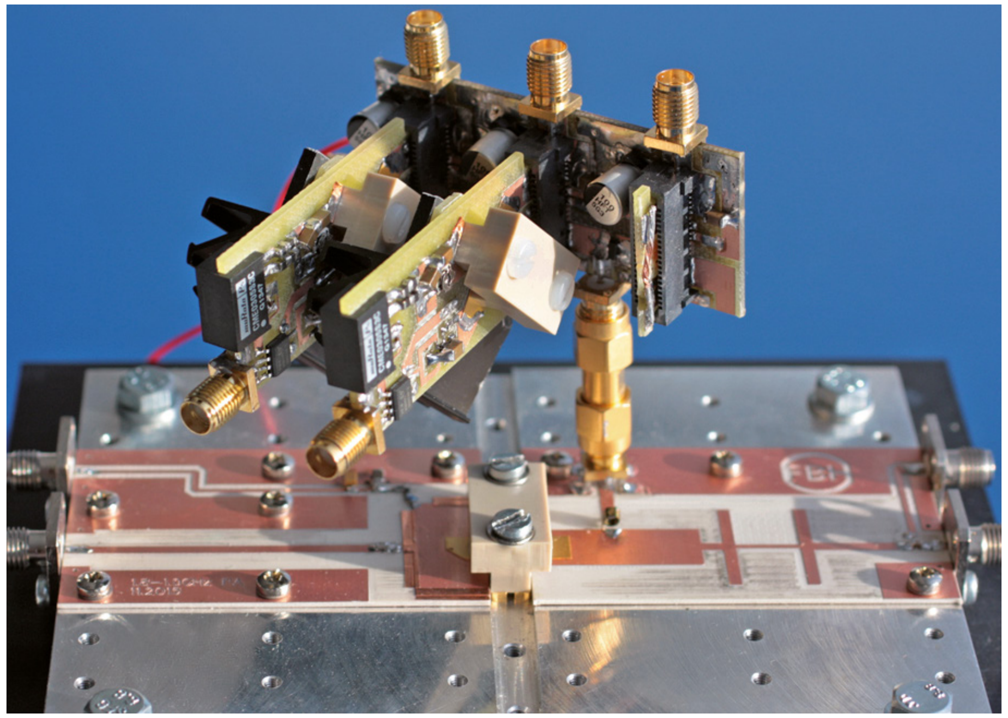


Fig. 3. Three-level class-G modulated RF power amplifier with 65 W peak output power for 1.8 - 1.9 GHz LTE applications.

The latest class-G system comprising the modulator and PA is working with up to three supply voltage levels and achieves high average efficiencies above 50 % for a 1.85 GHz LTE signal. This is an improvement of 19 percentage points compared to a single supply PA. When applying proper DPD the same linearity as for the conventional PA is measured. A photograph of this system is shown in Fig. 3.

This research activity "Class-G based envelope tracking system for high-efficiency transmitter modules in mobile communications" is supported by DFG (German Research Foundation), contract No. BE 5397/1-1 and HE 1676/21-1.

Die Forschungsarbeiten des FBH auf dem Gebiet der Klasse-G-Modulation zielen auf die Effizienzsteigerung von Hochfrequenz-Leistungsverstärkern in Basisstationen für die drahtlose Kommunikation. In Klasse-G-Systemen wird die Versorgungsspannung des Leistungsverstärkers dynamisch mit der momentanen Ausgangsleistung umgeschaltet. Dadurch lassen sich die Leistungsverluste bei niedriger Aussteuerung signifikant reduzieren. Hierfür werden am FBH spezielle Modulatoren für das Umschalten der Versorgungsspannung und die zugehörigen Leistungsverstärker entwickelt. Neben der Effizienz spielt beim Mobilfunk die Linearität des Leistungsverstärkers eine wichtige Rolle, um die Vorgaben der Standards zu erfüllen. Klasse-G-Modulation führt, aufgrund der Spannungsabhängigkeit der Verstärkungseigenschaften, zu starken Störungen des Sendesignals. Um diese zu korrigieren, wird mittels digitaler Vorverzerrung die Linearität wieder hergestellt. Hierfür werden spezielle, für Klasse-G optimierte digitale Vorverzerrer benötigt, die ebenfalls am FBH entwickelt werden.

Publications

N. Wolff, W. Heinrich, M. Berroth, O. Bengtsson, "A Three-Level Class-G Modulated 1.85 GHz RF Power Amplifier for LTE Applications with over 50% PAE", IEEE MTT-S International Microwave Symposium Digest (2016).

N. Wolff, W. Heinrich, O. Bengtsson, "A Novel Model for Digital Predistortion of Discrete Level Supply-Modulated RF Power Amplifiers", IEEE Microwave Wireless Components Letters, vol. 26, no. 2. pp 146-148, (2016).

N. Wolff, W. Heinrich, O. Bengtsson, "Challenges in the Design of Wideband GaN-HEMT based Class-G RF-Power Amplifiers," Proc. German Microwave Conference 2016, Bochum, Germany, Mar. 14-16, pp. 189-192, (2016).

N. Wolff, O. Bengtsson, M. Schmidt, M. Berroth, W. Heinrich, "Linearity Analysis of a 40 W Class-G-Modulated Microwave Power Amplifier", Proc. 45th European Microwave Conference, Paris, France, Sep. 7-10, pp. 1216-1219 (2015).

N. Wolff, W. Heinrich, O. Bengtsson, "Analysis of the Switching Threshold in Dual-Level Class-G Modulated Power Amplifiers", Integrated Nonlinear Microwave and Millimeter-wave Circuits Workshop, Taormina, Italy, Oct. 1-2 (2015).

Modulators for digital RF power amplifiers

Digital RF power amplifiers (PAs) are discussed as a solution to meet the steadily increasing demand for higher data rates and better coverage in mobile communications, especially in conjunction with pico- and femtocells. In contrast to their analog counterparts they can easily be reconfigured for different frequency bands, are lightweight, compact, more cost-effective and can, at least in theory, be very power efficient.

Fig. 1 shows a digital transmit chain with such a digital PA. The digital baseband is first fed into a modulator that modifies the > 10 bit wide baseband signal into a single-bit bitstream that is suitable to be amplified by the digital PA. After the PA, the analog transmit signal is restored by a simple bandpass filter. The modulator is an essential component since its capabilities directly define the quality of the restored signal, and it has a significant influence on the actual efficiency of the PA as well.

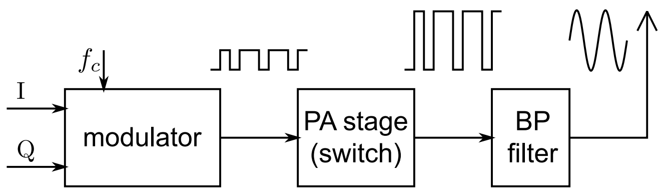


Fig. 1. Block diagram of digital transmitter.

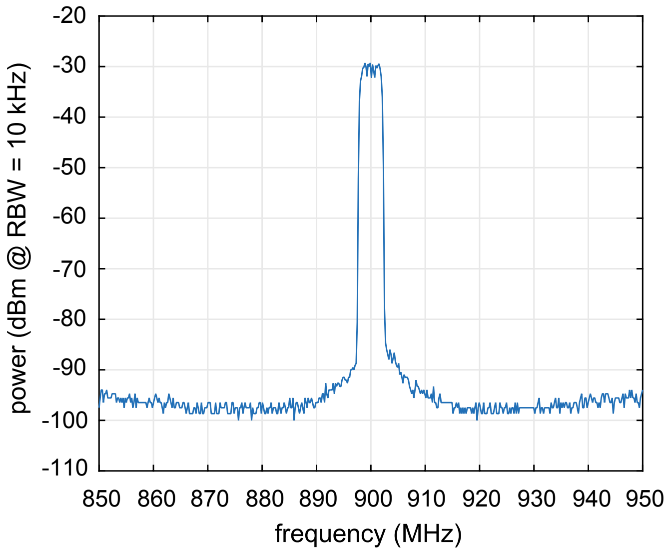


Fig. 2. Measured frequency spectrum.

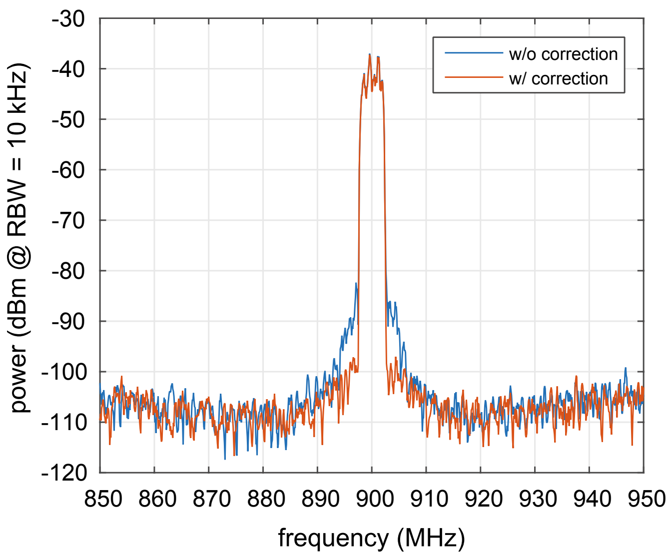


Fig 3. Measured frequency spectrum with amplifier.

The modulation schemes used for this purpose so far are mostly based on bandpass delta sigma (BPDSM) or pulse width (PWM) modulation. These are either very difficult or even impossible to implement in a digital circuit domain, or they struggle to meet the criteria concerning the signal purity like adjacent channel leakage power ratio (ACLR) and error vector magnitude (EVM). Also, when talking about highly efficient amplifiers in the range of a few ten watts, the power consumption of the modulator may become an important factor. All of the known modulator concepts miss the ability to correct for distortions caused by a non-ideal amplifier and therefore require a computationally intensive, power hungry digital predistortion (DPD).

The new modulator concept developed at the FBH not only improves the signal quality compared to already existing modulators, it also features the ability to correct for the most dominant amplifier distortions on its own, thus reducing the requirements for a complex DPD or even eliminating it entirely. The modulation can be adapted to the abilities of the pulse forming hardware in an actual implementation and can be tailored to specific properties of the amplifier. This could be the need for a certain minimum pulse length to ensure efficient operation, pulse-length dependent dead times or multiple inputs. In contrast to the commonly known bandpass delta sigma modulation (BPDSM) this modulator also maintains maximum coding efficiency, which is essential for any digital PA to reach decent power efficiency.

To prove feasibility of this modulator concept in a real world scenario the modulator was simulated in Matlab. The resulting waveforms were synthetized using an arbitrary waveform generator (AWG) and measurements were conducted on this signal to check the signal quality.

Fig. 2 shows the results, a 5 MHz wide WCDMA signal with 6.5 dB peak-to-average power ratio (PAPR) modulated onto a 900 MHz carrier and digitized into a single binary bit stream by the new modulator. It can be clearly seen that even with no correction for device-specific distortions the generated signal exhibits an ACLR of about 57 dB. Tab. 1 lists the measured ACLR values as well as the EVM.

Later, an available (analog) amplifier with subsequent attenuation was inserted to the signal path, deliberately adding distortions to the modulated signal, just like any digital PA might do. The resulting signal was measured, and a corrected set of coefficients for the modulator was derived from this

ACLR values for channel centered at				EVM	
890 MHz	895 MHz	905 MHz	910 MHz	RMS	Max
65.15 dB	61.00 dB	57.57 dB	63.70 dB	0.92 %	2.83 %

Tab. 1. Measured ACLR and EVM values over 5 MHz wide channels.

	ACLR values for channel centered at				EVM	
	890 MHz	895 MHz	905 MHz	910 MHz	RMS	Max
w/o correction	61.43 dB	48.46 dB	46.64 dB	62.06 dB	4.54 %	9.75 %
w/ correction	63.80 dB	58.63 dB	58.55 dB	63.71 dB	4.14 %	8.38 %

Tab. 2. Measured ACLR and EVM values over 5 MHz wide channels with amplifier.

measurement. When substituting the previously used (calculated) coefficients with these new ones, the modulator produces a signal precisely matching the characteristics of this particular amplifier. As a result, the distortions vanish, restoring ACLR values that are well comparable to those without amplifier, see Fig. 3 for the corresponding frequency plots and Tab. 2 for the measured key figures.

While the 3GPP specifications for cellular base stations only require 45 dB of ACLR in the adjacent channel the newly developed modulator has shown ACLR values clearly in excess of 55 dB in a real-world scenario. This provides comfortable headroom for any effects that might arise later when implementing this modulation scheme in an application-specific low-power signal processor chip. Overall, this development forms an essential and solid step towards competitive digital PAs.

This work is funded within the competitive procedure of the Leibniz Association under contract SAW 2015-FBH1.

Höhere Datenraten und eine noch bessere Netzabdeckung – das sind die Anforderungen an die Mobilkommunikation der Zukunft. Als vielversprechender Ansatz gelten digitale Leistungsverstärker (PA), deren Funktionsprinzip sich grundlegend von Analogverstärkern unterscheidet: Sie lassen sich sehr flexibel auf verschiedene Frequenzbänder einstellen. Zugleich können sie ebenso kostengünstig wie kompakt aufgebaut werden und sehr energieeffizient sein. Ein entscheidendes Element bei digitalen PAs ist der dafür notwendige Modulator. Er übersetzt das Basisbandsignal in einen rein binären Bitstrom, der anschließend vom PA mit möglichst hoher Effizienz verstärkt wird. Das FBH hat einen neuartigen Modulator entwickelt, der die Schwächen der bisher bekannten Modulatoren überwindet. Als Kerneigenschaften verfügt er über eine maximale Kodiereffizienz, erzeugt Signale mit sehr geringer Überkopplung in die Nachbarkanäle (ACLR) und besitzt die Fähigkeit, einen Großteil der Verzerrungen eines digitalen PAs direkt korrigieren zu können. Erste Laboruntersuchungen zeigen bereits sehr gute Ergebnisse.

III-V Electronics III/V-Elektronik

50 W GaN voltage-controlled oscillator as a basic module for future compact microwave power sources

From the beginning of microwave engineering, the generation of high-power signals has been a fundamental objective. Ever since, a variety of generator concepts has originated as a result of the different requirements regarding frequency, output power, purity and stability of the signal as well as efficiency concerns. So far, little attention has been paid to the amount of physical space that a module with a given output power consumes. Small size, however, is a key factor in the ongoing developments towards highly integrated, complex systems. Reducing the form factor opens new application fields such as dense microwave plasma arrays and distributed power sources for heating or EMV testing scenarios.

Recent research activities at FBH addressed the miniaturization of high-power generator modules, aiming at a substantial reduction in size, while simultaneously preserving the features and functionality of established concepts. As an alternative to the conventional concept, power oscillator circuits were chosen to solve this challenging task.

Previous work at FBH had led, as a first step, to ultra-small high-power oscillators operating at a fixed frequency. Until now, generators with variable frequency used to be the domain of low-power synthesizers which, in order to achieve high power levels, require a bulky amplifier cascade downstream. In continuation of this work, FBH now succeeded in realizing for the first time ever electronic frequency tuning of a high-power 2.45 GHz oscillator.

A prototype was designed (see Fig. 1) with the aim to cover the full 2.4 GHz ISM frequency band. The circuit uses two FBH GaN-HEMTs in a differential configuration (Fig. 2) and includes four anti-serial SiC Schottky varactor diodes, which facilitate the frequency tuning. The varactors are required to meet a unique combination of specs, i.e., high reverse breakdown voltage, large C_{max} / C_{min} ratio, and ultra-flat C/V-characteristics. The SiC Schottky diodes, provided by Chalmers University of Technology in Sweden, offered the best performance in this regard. The module delivers a total power well above 30 W, peaking at 56 W. Fig. 3 presents the results. Oscillator power is generated with an efficiency between 35 % and 54 %. A good performance

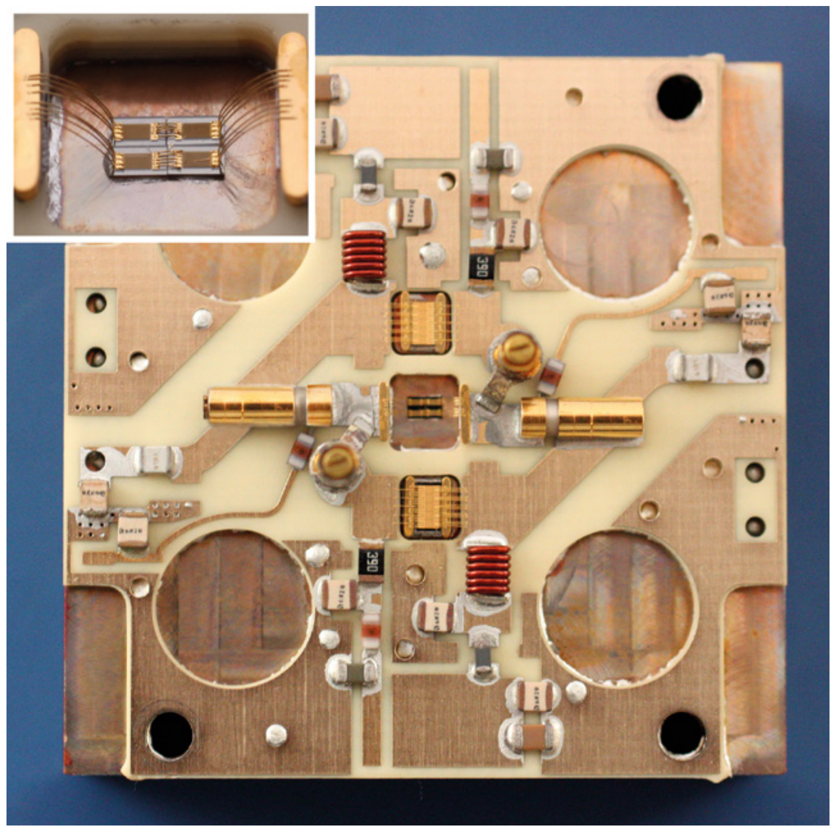


Fig. 1. Prototype of the voltage-controlled GaN power oscillator.

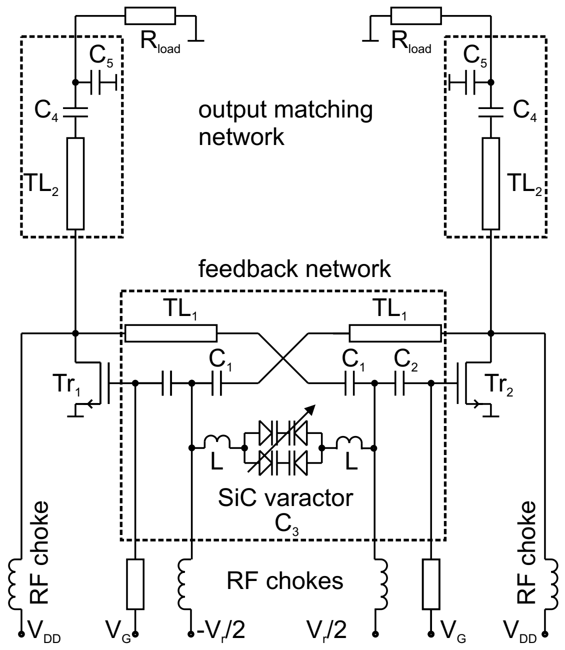


Fig. 2. Circuit topology of the GaN power oscillator with voltage-controlled frequency tuning based on SiC Schottky diode varactors.

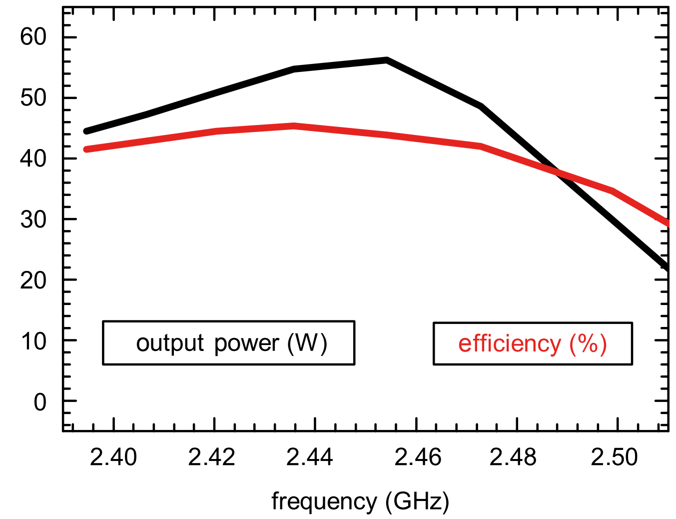


Fig. 3. Total output power and efficiency vs. oscillation frequency.

could also be demonstrated in terms of phase noise, which stays below -120 dBc/Hz at 1 MHz offset. Overall size is as low as 10 cm^2, which is a tenth of the area a comparable conventional generator occupies.

The VCO allows for integration into a miniaturized microwave plasma source, which is currently being realized within an industrial cooperation. The circuit offers a new solution to high-power microwave generation. Further research options include the investigation of alternative tuning elements such as barium strontium titanate (BST) varactors.

Für verschiedene technische Anwendungen müssen leistungsstarke Mikrowellensignale mit guter spektraler Reinheit und hoher Effizienz erzeugt werden. Im Trend zunehmender Miniaturisierung gewinnt zugleich die Generatorgröße an Bedeutung. Sie entscheidet über die Integrierbarkeit in kompakte Systeme und ist Grundlage für innovative Lösungen, beispielsweise von Array-Anordnungen im Bereich der Plasmaquellen. Um diesen Herausforderungen zu begegnen, entwickelt das FBH seit einiger Zeit Mikrowellengeneratoren, die auf Leistungsoszillatoren basieren und eine bedeutend geringere Schaltungsfläche als andere Konzepte erfordern. Es ist nun erstmals gelungen, mit der bislang fehlenden elektronischen Frequenzsteuerbarkeit einen wesentlichen Nachteil dieser Oszillatoren zu beseitigen. Ein Prototyp, der mit FBH-GaN-HEMTs und speziellen SiC-Schottky-Dioden der Chalmers University of Technology in Schweden ausgestattet ist, erreicht eine Abstimmbandbreite, die das gesamte 2,45 GHz ISM-Frequenzband abdeckt. Auf einer Fläche von nur 10 cm^2 liefert das Modul dabei mehr als 30 Watt Ausgangsleistung, die mit einer Effizienz von über 35 % erzeugt wird.

Publication

C. Bansleben, W. Heinrich, "Electronic frequency tuning of a high-power 2.45 GHz GaN oscillator", IEEE MTT-S Int. Microw. Symp. Dig., Phoenix, USA, May 17-22, WE4B-1 (2015).

SciFab – hetero-integrated InP DHBT / SiGe BiCMOS technology available as foundry service to customers

Heterogeneous integration of FBH's InP DHBT technology with SG25 BiCMOS technology provided by IHP (Frankfurt/O.) offers designers the 'power' of both worlds, thus advancing potential capabilities beyond state-of-the-art. This monolithic heterogeneous integration leads to a fully interwoven layer stack comprising all BiCMOS active and passive layers as well as all InP DHBT circuit layers, including three additional layers of interconnects. Both stack layers are interconnected using via holes with frequency capability beyond 300 GHz. The combined technology includes high-power InP DHBT devices with f_T & f_{max} above 320 GHz at 20 mA collector current and BV_{CEO} = 4 V breakdown voltage.

Meanwhile, a full design kit is available to circuit designers and external customers via IHP foundry service. The design kit, fabrication flow integration between FBH and IHP, and several fabrication process improvements were implemented in the framework of the three-year Leibniz SAW project SciFab, resulting in the commercial availability of the hetero-integrated mm-wave circuit process [1]. The design kit allows co-design of both technologies including simulation and layout, thus realizing true hetero-integration on circuit level. Customers can upload their completed design layout through IHP's foundry interface and, in turn, receive a number of chips diced from a multipurpose project wafer.

a b

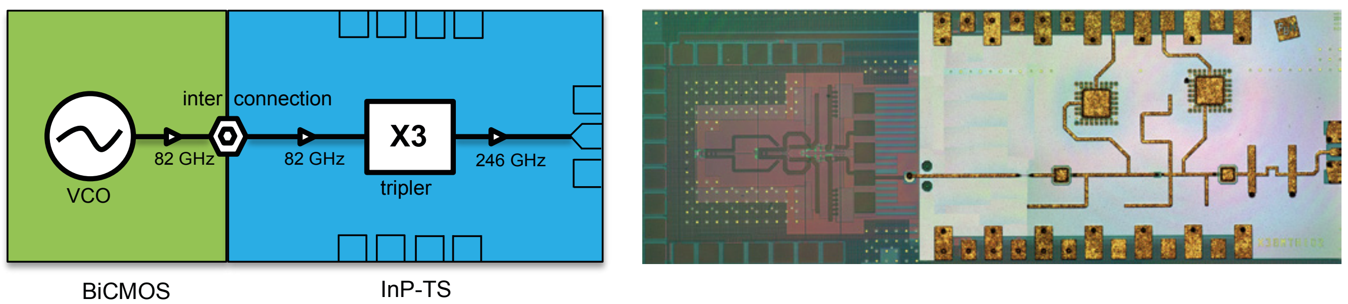


Fig. 1. Schematic (a) and photograph (b) of a 250 GHz integrated signal source.

A number of MMIC circuits have been designed in the SciFab process including signal sources and multipliers. As an example, we show two signal sources at 250 GHz (Fig. 1) and 330 GHz (Fig. 3), both based on a SiGe BiCMOS VCO followed by an InP frequency tripler and quadrupler, respectively. The hetero-integrated 250 GHz signal source [2] generates an output power of -1.6 dBm, with a phase noise of -85 dBc/Hz @ 1 MHz offset and -106 dBc/Hz @ 10 MHz. The related measurement results are shown in Fig. 2. The DC-to-RF efficiency is 4.6 % with a chip area of 3.0 mm². This chip area can now be substantially decreased by overlapping of both technologies. The 330 GHz quadrupler signal source [3] is based on an 82 GHz BiCMOS VCO, followed by a balun, a driver, and a quadrupler circuit. It delivers an output power of -12 dBm @ 328 GHz while occupying a chip area of only 2.5 mm². See also measurement results in Fig. 3. More recent circuits tend to be even smaller.

SciFab allows for thermal dissipation from the InP layers to the BiCMOS side using appropriate vias (see also p. 106). FBH has also introduced a heat spreader technology to achieve even higher output powers with amplifiers using diamond heterogeneous integration. InP HBT transistors with this heat spreader technology exhibit a thermal resistance decrease by a factor of two. Experimental results for the power amplifiers demonstrate record output powers of more than 200 mW and improved power-added efficiencies of 15 % at W-band.

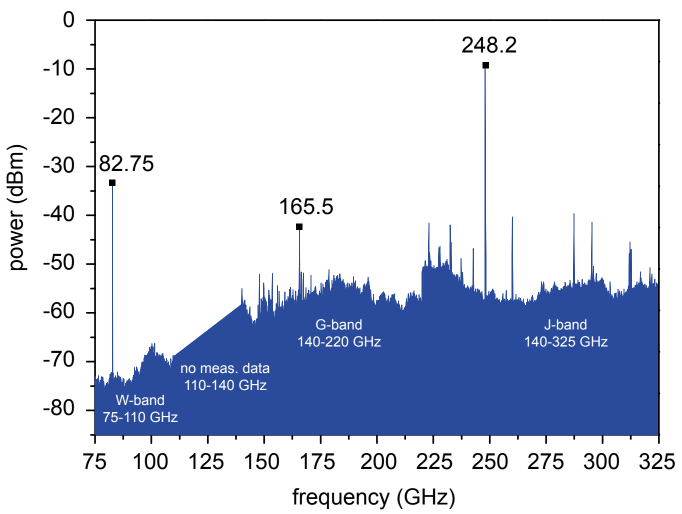


Fig. 2. Measured results for the 250 GHz integrated signal source.

a b

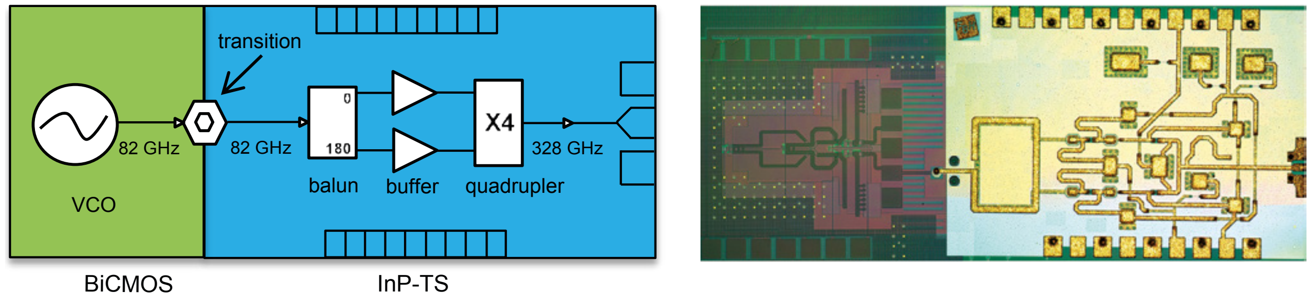


Fig. 3. Schematic (a) and photograph (b) of a 330 GHz integrated signal source.

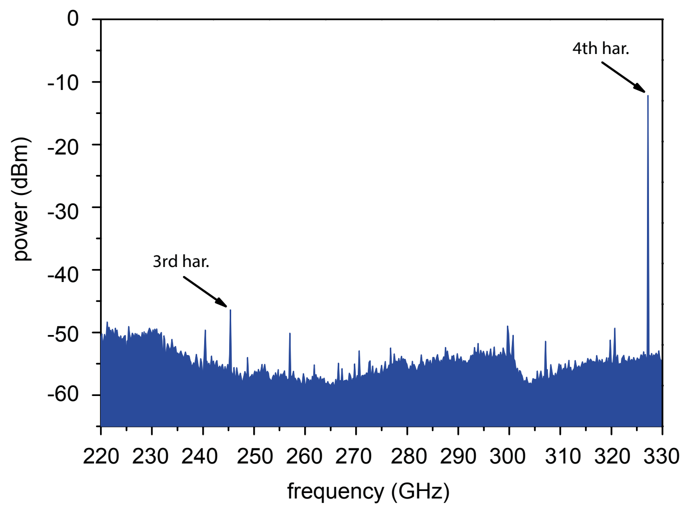


Fig. 4. Measured output spectrum for the 330 GHz integrated signal source.

Publications

[1] N.G. Weimann, D. Stoppel, M.I. Schukfeh, M. Hossain, T. Al-Sawaf, B. Janke, R. Doerner, S. Sinha, F.-J. Schmückle, O. Krüger, V. Krozer, W. Heinrich, M. Lisker, A. Krüger, A. Datsuk, C. Meliani, B. Tillack, "SciFab –a wafer-level heterointegrated InP DHBT/SiGe BiCMOS foundry process for mm-wave applications", Phys. Status Solidi A. doi: 10.1002/pssa.201532549 (2016).

[2] M. Hossain, N. Weimann, B. Janke, M. Lisker, C. Meliani, B. Tillack, O. Krüger, V. Krozer, W. Heinrich, "A 250 GHz hetero-integrated VCO with 0.7 mW output power in InP-on-BiCMOS technology", European Microwave Conference (EuMC), pp. 391 - 394, doi: 10.1109/EuMC.2015.7345782 (2015).

[3] M. Hossain, N. Weimann, M. Lisker, C. Meliani, B. Tillack, V. Krozer, W. Heinrich, "A 330 GHz hetero-integrated source in InP-on-BiCMOS technology", IEEE MTT-S Intern. Microwave Symposium (IMS), 2015, doi: 10.1109/MWSYM.2015.7166907 (2015).

Die Heterointegration der InP-DHBT-Technologie des FBH mit der SG25-BiCMOS-Technologie des IHP (Frankfurt/O.) ermöglicht neuartige Schaltungen, die die positiven Eigenschaften beider Technologien vereinen. Dies führt zu Leistungssteigerungen über den aktuellen Stand der Forschung hinaus. Dank der monolithischen Integration kann zwischen den beiden Technologien mit gezielt entwickelten Durchführungen (Vias) gewechselt werden. Zusätzlich stehen drei weitere Verdrahtungsebenen gegenüber der reinen BiCMOS-Technologie zur Verfügung. Die Durchführungen sind auf 300 GHz ausgelegt, wobei die InP-DHBT-Transistoren f_T & f_{max} oberhalb von 320 GHz bei 20 mA Kollektorstrom und BV_{CEO} = 4 V Durchbruchspannung besitzen. Der zugehörige Design Kit ermöglicht es, gleichzeitig in beiden Technologien zu arbeiten. Dieser Foundry Service ist externen Nutzern über das IHP zugänglich. Eine Reihe von Schaltungen wurde bereits in SciFab realisiert, insbesondere Signalquellen bei 250 GHz mit -1,6 dBm Ausgangsleistung und -85 dBc/Hz @ 1 MHz sowie eine Reihe von Frequenzvervielfachern bis 330 GHz. Die InP-Schaltungen können direkt über die BiCMOS-Schaltungen gelegt werden, wodurch die benötigte Chipfläche weiter reduziert werden kann.

III-V Electronics III/V-Elektronik

Metrology results – accuracy issues for calibrated on-wafer S-parameters in mm-waves up to 500 GHz

The development of high-frequency circuits continuously pushes the upper frequency limits. Recently, integrated circuits up to the 500 GHz range have been demonstrated, the majority of them being realized as monolithic-integrated circuits on III-V semiconductors or silicon. In a first step, the characterization of these circuits is carried out on the wafer using suitable probe tips. However, these probe tips contribute parasitics corrupting the measured data, which becomes increasingly severe at frequencies beyond 100 GHz. Consequently, their influence must be taken into account and subtracted in order to determine the properties of the actual circuit. This is supported by so-called calibration techniques, based on the measurement of a certain set of transmission-line structures. Due to the current technologies and in view of cost-effective packaging, transmission-line types like coplanar or microstrip waveguides are preferably used. However, using these line types becomes critical with growing frequency. Especially the environment formed by the testing methods degrades accuracy of the measurement. This is related to parasitic effects like excitation of extra modes, radiation, reflections, and resonances.

The formation of these parasitic effects depends on the structures themselves but also on chip technology and environment (support, housing, etc.). Therefore, it is important to have a closer look into the measurement system. The applied probe tips, also called probes, are fed by a hollow or coaxial waveguide and usually end in a coplanar system of three contact tips. These tips touch down aslant on appropriate metal pads of the device under test. Figs. 1a and c show a probe touching different line structures. Obviously, such a probe system perturbs the wave propagation, causing reflections and exciting unwanted modes. The present research aims at minimizing and ideally avoiding effects caused by probes. This could be achieved by an optimally designed probe tip and/or by choosing a more appropriate line system. Additionally, shielded lines are generally recommended with increasing frequency since they prevent radiation. Their fabrication involves more technological steps due to extra metal layers and via connections, but the shielding guarantees superior electrical behavior up to 500 GHz and beyond. Figs. 1b and d illustrate radiation into the substrate using identical probes for a coplanar waveguide (CPW) and a shielded stripline structure, respectively. While the stripline structure is distinguished by low radiation, its pad layout is designed specifically to minimize radiation. The resulting enhancement can directly be observed in the line parameters. As expected theoretically, the propagation constant exhibits a smooth behavior as a function of frequency. In contrast, the parameters of structures with strong parasitic effects show distinct deviations from the ideal characteristics.

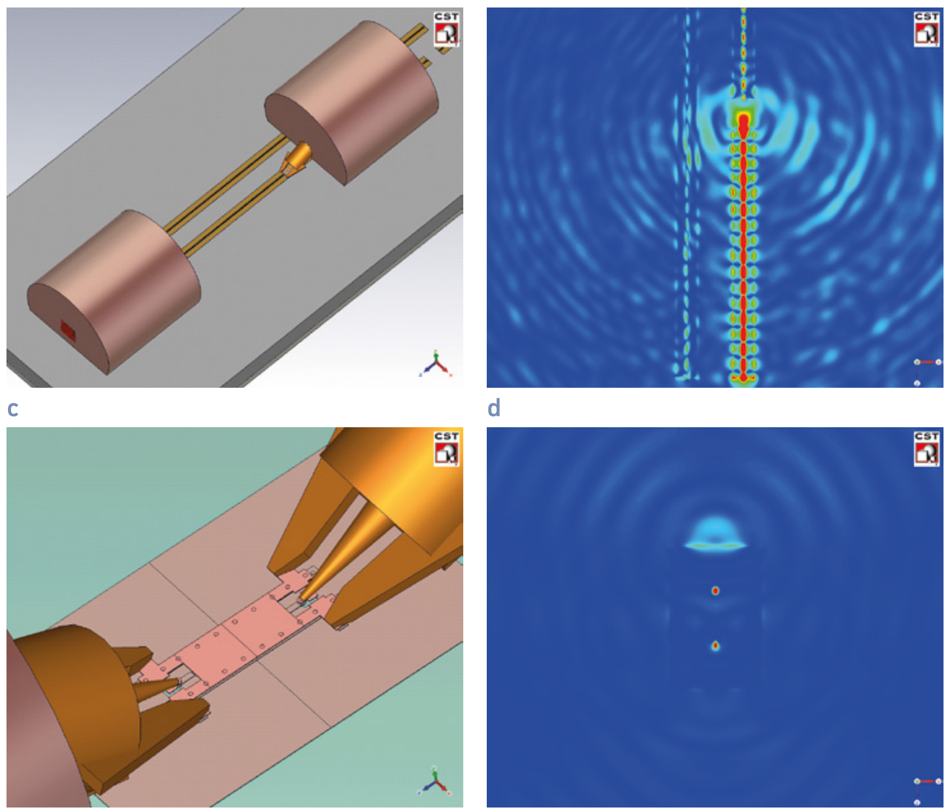


Fig. 1. Measurement set-ups of calibration line structure and probe tips. (a) Coplanar waveguide (CPW); (b) Field plot of (a) (in a plane directly beneath the CPW metallizations); (c) Shielded stripline; (d) Field plot of (c) (in a plane directly beneath the lower ground plane).

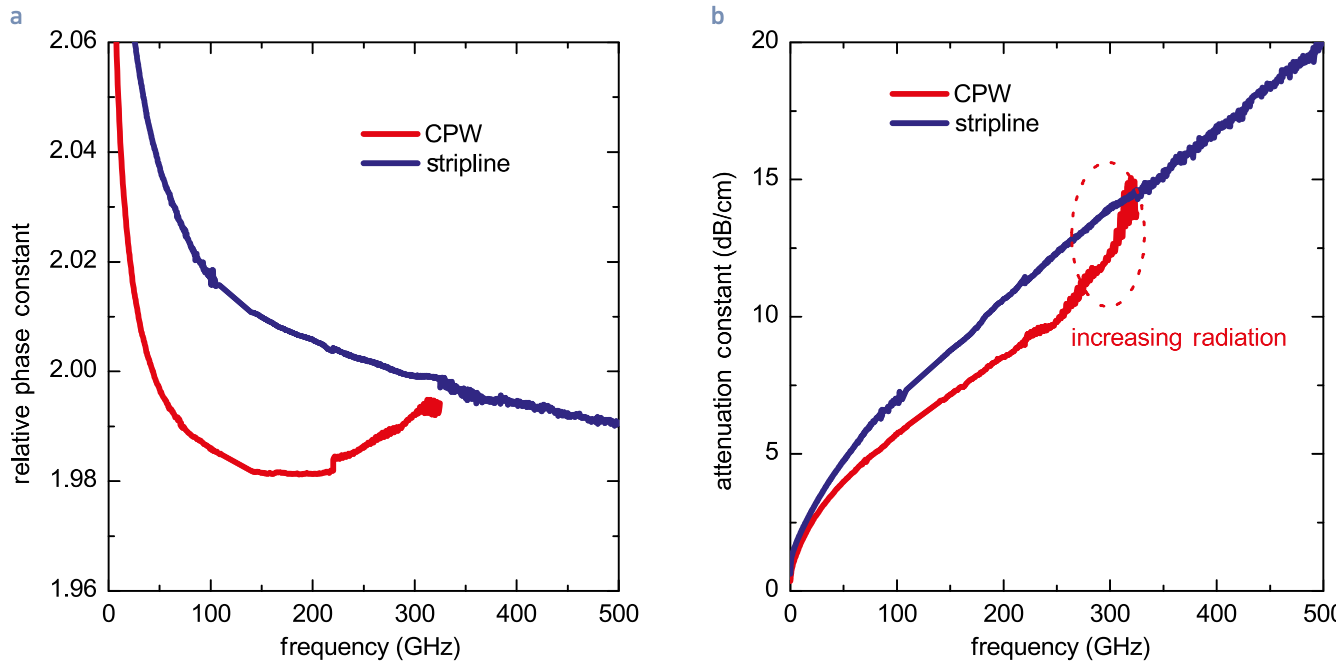


Fig. 2. Line parameter comparison of coplanar waveguide and shielded stripline, (a) relative phase constant, (b) attenuation constant.

Fig. 2 compares the transmission line parameters of a coplanar waveguide and a shielded stripline. The effect of increasing radiation at higher frequencies can clearly be recognized by the disproportional rise in attenuation. Metrology, i.e., the derivation of standards for measurement methods and the determination of their reproducibility demands for highest accuracy and repeatability and thus needs special care to minimize parasitics. However, the effects described above are critical already for the everyday measurement practice. Everyone performing on-wafer measurements in higher mm-wave frequency range is confronted with this difficulty.

The FBH is involved in several projects with companies and institutions in Europe and worldwide, including a European metrology project. These projects deal with the improvement of the calibration methods as well as with the proper design of the setups themselves. The activities regarding metrology for new electrical measurement quantities in high-frequency circuits are funded by the European Metrology Research Program EMRP.

Publication

D.F. Williams, F.-J. Schmückle, R. Doerner, G.N. Phung, U. Arz, W. Heinrich, "Crosstalk Corrections for Coplanar-Waveguide Scattering-Parameter Calibrations", IEEE Trans. Microwave Theory Tech., vol. 62, no. 8, pp. 1748-1761 (2014).

Neu entwickelte Hochfrequenzschaltungen erschließen immer höhere Frequenzen. Inzwischen haben sich Anwendungen bis 500 GHz etabliert, für die häufig monolithisch-integrierte Schaltungen auf einem Halbleiter-Chip realisiert werden. Die messtechnische Charakterisierung dieser Schaltungen und ihrer Komponenten erfolgt zumeist direkt auf dem Wafer. Jedoch können die gegenwärtig verwendeten Messmittel das ursprüngliche Verhalten der Messobjekte so ungünstig beeinflussen, dass klassische Korrekturmethoden scheitern. Diese unerwünschten parasitären Effekte werden am FBH detailliert untersucht, um sie zu beschreiben und Methoden zu ihrer Eliminierung zu finden. Erwartungsgemäß stellt die Metrologie, d.h. die Herleitung von Standards für Messverfahren und die Bestimmung von deren Reproduzierbarkeit, besonders hohe Anforderungen an Genauigkeit und Wiederholbarkeit. Doch bereits in der allgemeinen Messpraxis bei On-Wafer-Messungen in höheren Frequenzbereichen zeigen sich die Folgen der Problematik – meist in Form von nicht erklärbaren Messergebnissen. Das FBH ist an mehreren Projekten europa- und weltweit beteiligt, die Wege zu geeigneteren Verfahren suchen und anhand von Simulationen Vorschläge für neue, verbesserte Designs der Messobjekte und -anordnungen erarbeiten.

III-V Electronics III/V-Elektronik

Sputtered gate technology for low-dispersive and highly reliable GaN MMICs up to Ka-band

Low-dispersive and highly reliable GaN-based transistors are the pre-requisite for implementing GaN-based monolithic microwave integrated circuits (MMIC) into space systems for satellites. Therefore, considerable work has been put into developing a new gate technology, which has the potential of further cutting down device leakage currents, strongly reducing dispersion effects and, last but not least, improving the overall device reliability. Two main trapping effects adversely affecting device performance are known to be present in GaN HFETs, i.e., buffer and surface trapping. Buffer layer trapping usually relates to the quality of the epitaxial layers and becomes clearly visible during drain lag measurements. In contrast, gate lagging points to the trap states either under the gate or in close vicinity to the gate. In any case, lagging effects significantly deteriorate microwave performance of GaN devices and thus need to be minimized. The increasing demands towards highly linear GaN power amplifiers operating at Ka-band frequencies and above call for extremely low dispersive devices. Such devices based on FBH´s novel sputtered gate technology have now been demonstrated. This technology can be used to fabricate 500 nm, 250 nm, and 100 nm gate lengths depending on the targeted application frequency from L- to Ka-band.

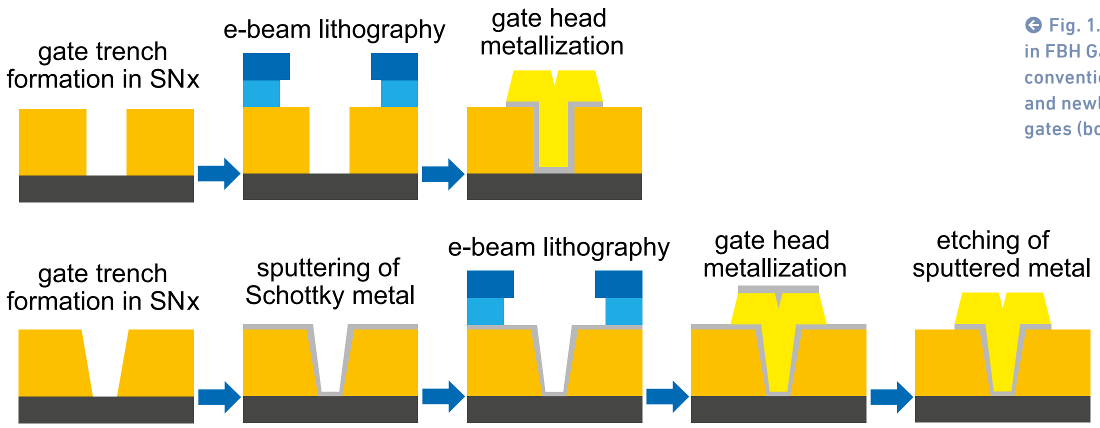


Fig. 1. Gate module process flow in FBH GaN-based MMIC technology: conventional evaporated gates (top) and newly developed sputtered gates (bottom).

Fig. 1 schematically shows the process flow of gate formation and compares the originally applied evaporated gate technology to the newly developed sputtered version. Advantage of the new gate module is that the gate trench can be coated by a chemically inert material (iridium in our case) immediately after trench etching without being subjected to additional lithographic steps as it is necessary in the conventional 'evaporated' version. This significantly reduces the risk of chemical contamination of the semiconductor surface in the open trench. Furthermore, the metal sputtering process creates a conformal coverage of the gate trench including the sidewalls eliminating void creation in this very sensitive device region. The new gate module starts with the formation of a slanted gate trench profile in the SiN_x layer. It supports trench openings from 100 nm to 500 nm and includes e-beam lithography in ZEP resist with subsequent thermal reflow and ICP plasma etching in a CHF_3/SF_6 gas mixture.

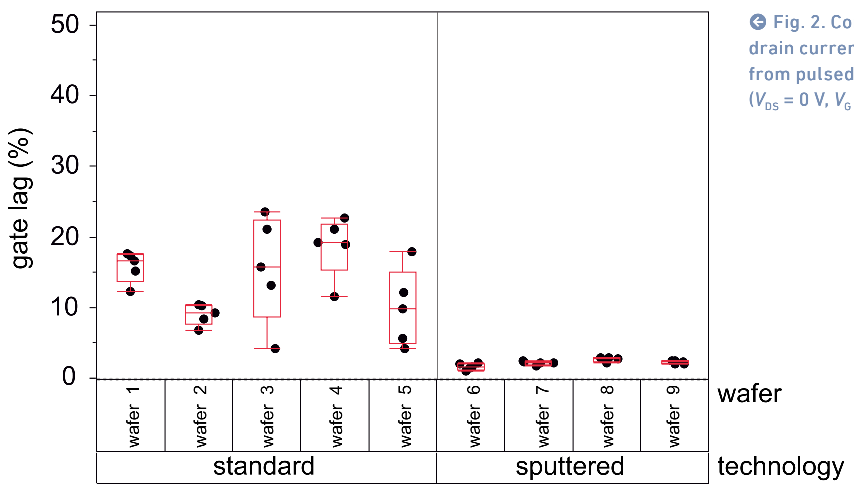


Fig. 2. Comparison of gate technologies by means of gate lagging: drain current reduction in percentage shown at V_{DS} = 10 V, V_G = 1 V from pulsed *I-V* characteristics measured at quiescent bias points (V_{DS} = 0 V, V_G = 0 V) and (V_{DS} = 0 V, V_G = -7 V).

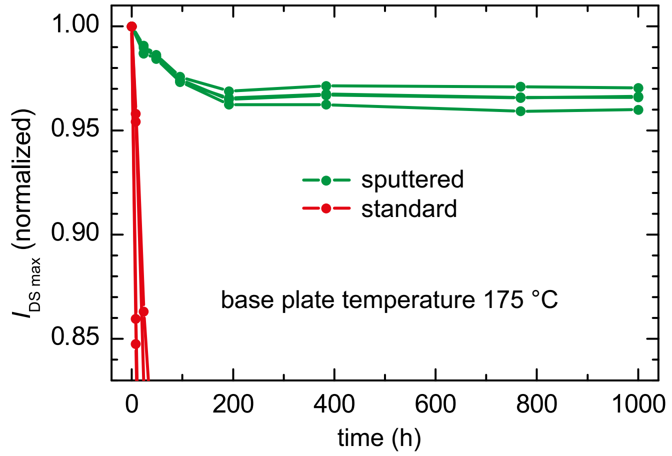


Fig. 3. Comparison of gate technologies in terms of the decay of $I_{DS\ max}$ normalized to its original value versus duration of lifetime tests at $T_{base\ plate}$ = 175°C, V_{DS} = 30 V and I_{DS} = 150 mA/mm constantly maintained during the test.

Metallizing the gate trench without intermediate lithography step forms an ideally clean metal-semiconductor interface, which, in turn, should lead to the formation of a better gate Schottky contact. This is visible in excellent *I-V* diode characteristics with a Schottky barrier height of 0.9 – 1.1 eV and a linear current increase in the half-log representation over 7 orders of magnitude. The ideal metal-semiconductor interface results in the reduction of the gate lag measured by pulsed *I-V* method. Fig. 2 shows the comparison of the gate lag measured on the wafers processed with standard and sputtered technologies. The gate lag in average reduces from 14 % to 2 % for standard and sputtered technology, respectively.

Conformal metal coverage of the gate trench prevents void formation at the triple point gate metal, passivation, and semiconductor surface. Such voids are very critically affecting device lagging and reliability by both local increase of the electric field and possible interaction of metals additionally included in the gate metal stack (e.g., Au) with SiN_x and the semiconductor surface. As a result, improved field and thermal stability of the transistors were observed. The results of an accelerated DC lifetime test at base plate temperature 175°C are shown in Fig. 3. An excellent stability (in the range of 5 %) of the maximum drain current over 1,000 hours DC aging was measured for the transistors fabricated with the newly developed gate module. In contrast, transistors fabricated using the conventional evaporated gate module prone to a continuous degradation of the drain current are reaching the limit of 10 % in the first 50 – 100 hours.

Am FBH wurde eine neuartige Technologie für die Herstellung von Gate-Elektroden in GaN-HEMT-Bauelementen entwickelt. Dabei wird die bisher durch Elektronenstrahlverdampfen aufgebrachte Ir-Schicht mittels Sputterdeposition erzeugt. Dieses Verfahren ermöglicht eine lunkerfreie und potenziell stressärmere Funktionsschicht als Schottky-Metall für die Transistor-Gates. GaN-HEMTs mit Gate-Längen von 500 nm, 250 nm und 100 nm wurden hergestellt – je nach Betriebsfrequenz im L- bis Ka-Band. Die Gate-Dioden zeigen eine hohe Schottky-Barriere von 0,9 bis 1,1 eV und in der halblogarithmisch aufgetragenen Vorwärtscharakteristik einen über sieben Größenordnungen linearen Bereich des Stroms. Die Reduktion des Transistorstroms im gepulsten Betrieb („gate lagging" bzw. Dispersion verursacht durch Umladeeffekte in Haftstellen) wurde auf 2 % verringert im Vergleich zu 14 % bei bisherigen Verfahren. Ferner zeigen die so hergestellten GaN-HEMTs eine deutlich verbesserte Stabilität: Bei thermisch beschleunigter Alterung verringerte sich der Transistorstrom nach 1.000 Stunden Betriebszeit nur um ca. 5 % gegenüber dem Ausfall der bisher hergestellten GaN-HEMTs (definiert als 10 % Stromabfall) in den ersten 50 bis 100 Stunden.

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", Int. Conf. on Compound Semiconductor Manufacturing Technology (CS ManTech), Denver, USA, May 19-22, pp. 189-192 (2014).

R. Lossy, H. Blanck, J. Würfl, "Sputtered Iridium Gate Module for GaN HEMT with Stress Engineering and High Reliability", Int. Conf. on Compound Semiconductor Manufacturing Technology (CS ManTech), Denver, USA, May 19-22, pp. 189-192 (2014).

III-V Electronics III/V-Elektronik

600 V GaN-on-Si power transistors with improved static and dynamic switching properties for power electronic applications

High-voltage gallium nitride (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 to the low area-specific on-state resistance for a given blocking strength and the low gate charge required for switching. FBH uses a standardized processing scheme for manufacturing GaN-based 600 V/70 mΩ normally-off switching transistors for power electronic applications. These devices outperform current state-of-the-art Si-based superjunction MOSFETs in terms of gate charge, switching energy, and needed chip area.

Apart from GaN-on-SiC wafers, 4" GaN-on-Si wafers (Fig. 1) are used for the FBH GaN transistors. Due to low substrate costs and large wafer diameters such wafers are the precondition for cost-efficient GaN transistors. Moreover, they are compatible with existing Si-device production lines. Normally-off transistor characteristic is mandatory for power electronic applications, and the inherently normally-on GaN HFETs get converted to normally-off by means of a p-GaN gate module. FBH has developed normally-off GaN-HFETs for Si and SiC substrate materials with p-GaN gate modules controlling the transistor current in a similar fashion (Fig. 2).

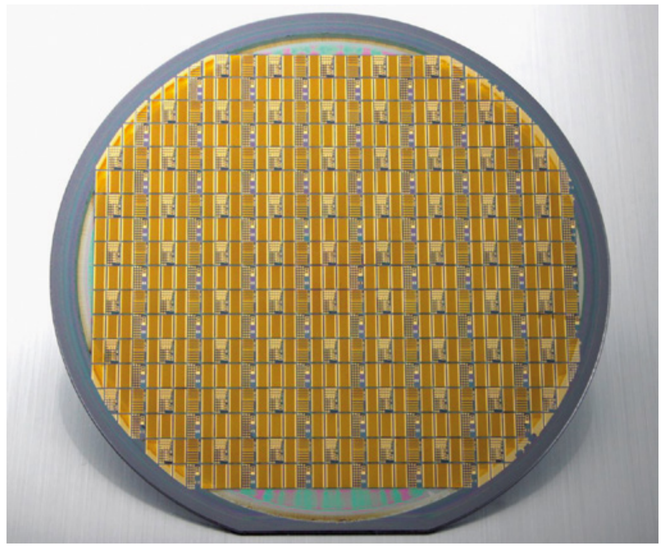


Fig. 1. 4" GaN-on-Si wafer with normally-off 600 V/70 mΩ transistors.

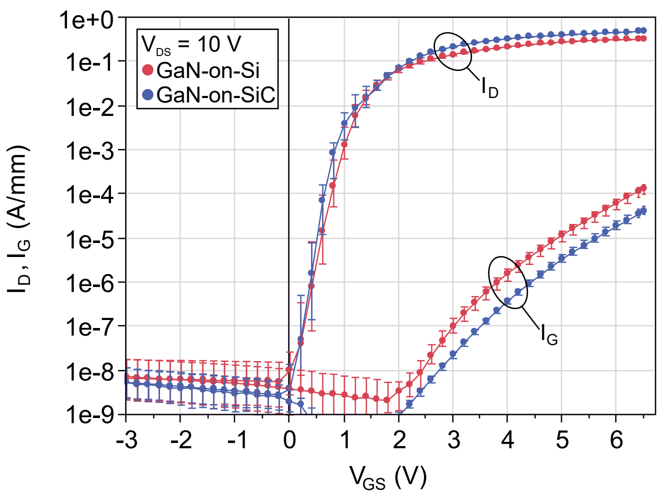


Fig. 2. Transfer characteristics (drain current I_D and gate current I_G) of normally-off GaN transistors based on GaN-on-Si (red) and GaN-on-SiC wafers (blue). Wafer medians and scatter are shown.

600 V GaN-on-Si transistors with 214 mm gate width feature 90 A pulse current (Fig. 3) and 61 mΩ on-state resistance.

GaN-on-Si epitaxy for 600 V AlGaN/GaN HFETs is particularly challenging. As compared to other substrate materials (i.e. sapphire or SiC), silicon has a larger lattice and thermal expansion coefficient missmatch with respect to GaN. This makes the strain management for thick GaN layers crucial and the resulting wafer bowing limits the GaN buffer thickness to approx. 5 - 6 µm. On the other hand, thick GaN buffer layers are needed for high-voltage isolation since silicon substrates are conductive. Incorporation of deep acceptor traps by using carbon or iron doping is a common approach to still achieve the required breakdown strength. However, the introduced trap states may charge up during high-voltage off-state device condition and the trapped charges degrade the transistor channel conductivity after switching the transistor to on-state. This dispersion phenomenon is known as dynamic on-state resistance (R_{ON}) increase and adds switching and conduction losses in converter operation. To minimize the dynamic R_{ON}, the doping profile and other growth parameters have to be adjusted properly.

The dynamic R_{ON} increase of FBH transistors is determined from switching experiments with an inhouse developed test set-up up that operates up to 1000 V and 1 A. Drain voltage and drain current transients in the microsecond range are monitored during high-voltage switching events. The dynamic R_{ON} usually increases with off-state drain voltage and was determined as factor 1.8 and factor 1.3 for 400 V switching of two GaN-on-Si wafers with different carbon doping profile (Fig. 4). The observed dynamic R_{ON} reduction of wafer B for V_{DS} > 430 V can be understood in terms of GaN buffer discharging via the substrate.

During switching operation in a converter internal transistor on-state losses and switching losses will heat up the device. Both maximum drain current and R_{ON} then degrade since the electron mobility decreases with temperature. This effect is more pronounced for GaN-on-Si devices than for GaN-on-SiC since Si has a 3 times lower thermal conductivity as compared to SiC.

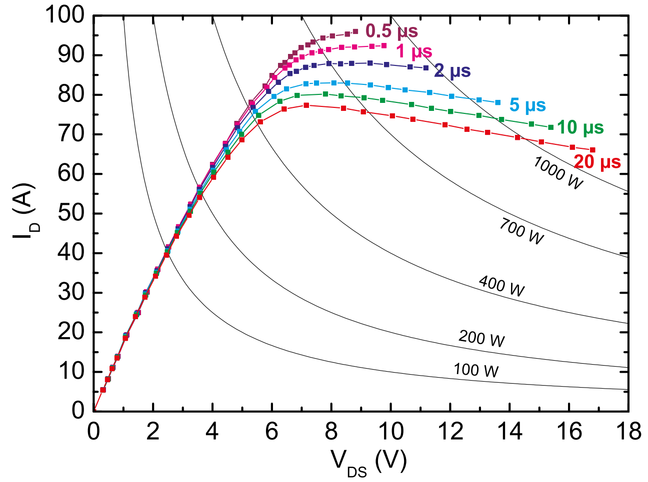


Fig. 3. Pulsed on-state (V_{GS} = 5 V) IV-curves for a normally-off GaN-on-Si transistor with 214 mm gate width. Pulse lengths are 0.5 µs to 20 µs.

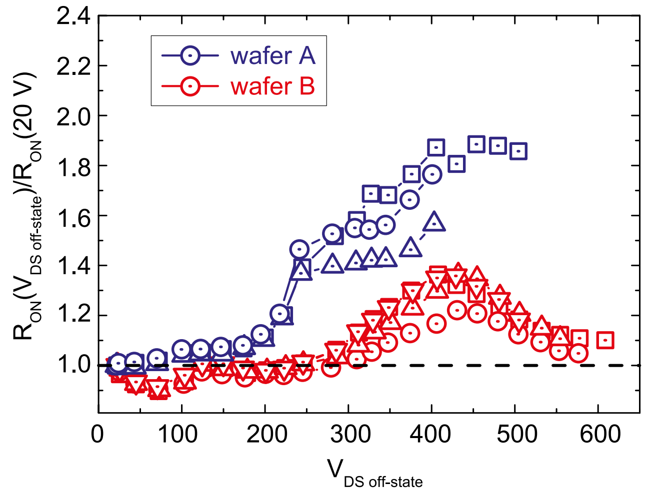


Fig. 4. Dynamic R_{ON} increase after off-state drain bias for two GaN-on-Si wafers with different buffer doping profiles.

Pulsed IV-curves with power dissipations up to 1000 W and pulsing times between 0.5 µs and 20 µs (Fig. 3) clearly demonstrate this effect for a 70 mΩ/600 V GaN-on-Si transistor. Significant current reduction due to self-heating at longer pulse times is detected for power levels > 300 W. However, no significant effect was observed at pulse powers < 200 W. A typically targeted converter application scenario for these devices would be 400 kHz switching of 25 A/400 V with 20 ns rise and fall times. The generated switching losses and on-state conduction losses are then in the order of 40 - 80 W only, and the transistor self-heating is of negligible impact on the on-state resistance.

Für Anwendungen in der Leistungselektronik stellt das FBH selbstsperrende 70 mΩ/600 V Galliumnitrid-Schalttransistoren her – sowohl auf Basis von GaN-auf-SiC- als auch auf 4" GaN-auf Si-Wafern. Basis dafür sind standardisierte Prozessmodule. Das dafür zwingend nötige selbstsperrende Verhalten wird dabei durch ein p-GaN-Gatemodul erzeugt. Dieses zeigt auf beiden Substratmaterialien, sowohl im Drain- als auch im Gatestrom, eine vergleichbare Übertragungscharakteristik. Für 600 V GaN-auf-Si-Transistoren muss das Kompensationsdotierungsprofil im GaN-Puffer genau eingestellt werden, um einen erhöhten dynamischen Einschaltwiderstand (R_{ON}) beim Hochspannungsschalten zu vermeiden. Mit der FBH-Transistortechnologie konnte die maximale dynamische R_{ON}-Erhöhung für 400 V Sperrspannung auf den Faktor 1,3 begrenzt werden. Jedoch weist Silizium einen 3-mal größeren Wärmewiderstand als Siliziumcarbid auf. Die Selbsterwärmung der GaN-auf-Si Transistoren kann daher ihre Eignung als Schalttransistor beeinträchtigen. Die Analyse von gepulsten Kennlinien bis 1000 W und bis 20 µs Pulsdauer zeigt aber keine relevante Degradation des Stroms für typische 400 kHz Schaltanwendungen bei 25 A und 400 V.

Publications

O. Hilt, E. Bahat-Treidel, A. Knauer, F. Brunner, R. Zhytnytska, and J. Würfl, "High-voltage normally OFF GaN power transistors on SiC and Si substrates", MRS Bull., vol. 40, no. 05, pp. 418-424 (2015).

O. Hilt, R. Zhytnytska, J. Böcker, E. Bahat-Treidel, F. Brunner, A. Knauer, S. Dieckerhoff and J. Würfl, "70 mΩ/600 V Normally-off GaN Transistors on SiC and Si Substrates", Proc. 27th International Symposium on Power Semiconductor Devices & IC's, May 10-14, Hong Kong, China, pp. 237-240 (2015).

Static and dynamic characteristics of quasi-vertical GaN power transistors

New gallium nitride (GaN) based power switching transistors enable efficient power converters with increased power density up to 600 V. High converter switching frequencies can be realized with GaN-based HFETs due to the low area-specific on-state resistance for a given blocking strength and the low gate charge required for switching. Conventional silicon (Si) based 600 V super-junction MOSFETs (and also SiC-based MOSFETs) have a vertical device scheme with the source placed on the chip front side and the drain on the chip back side. In contrast, GaN HFETs feature a lateral device scheme with both source and drain on the front side. The lateral scheme offers advantages for on-chip integration of gate drivers and free-wheeling diodes with the power switch. Integrated half-bridge modules with low inductance can get realized. However, a significant fraction of the expensive chip area is abandoned for on-chip wiring and bond-pads.

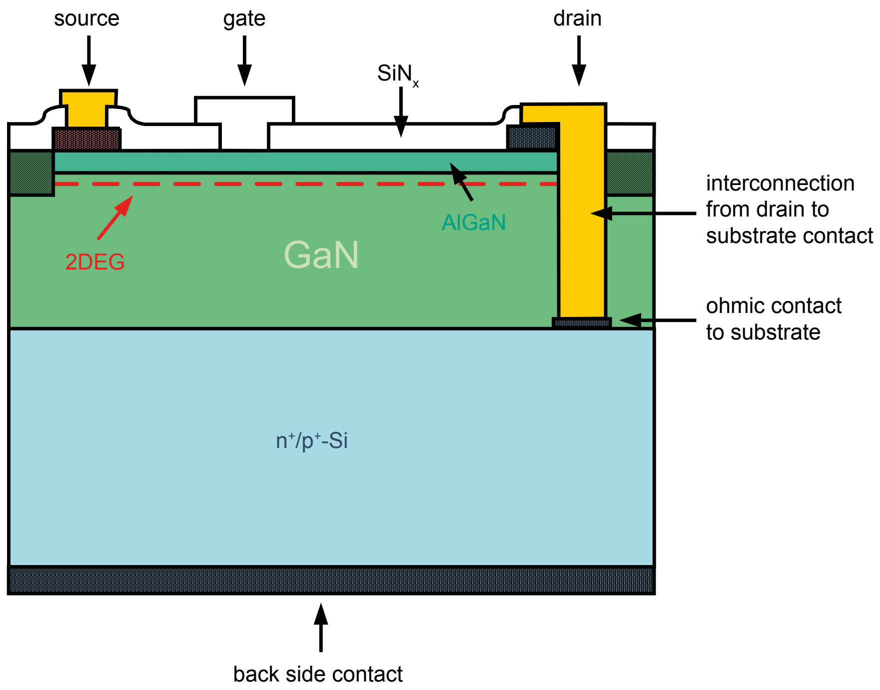


Fig. 1. Scheme for a drain-down connected quasi-vertical GaN-HFET; a source-down connected version is produced similarly.

FBH has developed a quasi-vertical integration approach for GaN HFETs that allows to flexibly bend either the source or the drain potential of individual transistor cells to the wafer back side. Thus, less chip area is used for wiring, inductances are reduced, and the high drain voltage is separated from the low source voltage on the respective chip sides. Additionally, the high flexibility of the lateral GaN HFET concepts is still preserved. In some cases it can be even increased, i.e., when connecting the high-side and low-side transistors of a half bridge on one chip via the chip back side.

On the GaN-on-Si wafers, via trenches through the GaN layers are used to connect either the drain or the source fingers to the highly conductive silicon substrate and thus to the substrate back side. Two finger normally-on GaN switching test transistors with 2.1 mm gate width have been produced on 4 inch GaN-on-Si wafers. To provide a metallic interconnect to the Si substrate a low resistive ohmic contact has been developed. A 5 µm thick Au metallization fills the trench completely and connects the upper GaN ohmic contact to the trench bottom ohmic contact. The quasi-vertical technology shows no degradation of the device on-state properties. The median on-state resistance of the quasi-vertical devices was measured as 11.7 ± 2.0 Ωmm. Corresponding lateral devices show an on-state-resistance of 12.7 ± 1.3 Ωmm.

An increased dynamic on-state resistance (R_{ON}) when switching from high-voltage off-state conditions is still a general issue of high-voltage GaN transistors. High internal electric fields combined with electronic trap states inside the GaN buffer due to compensation doping and structural defects lead to buffer charging when applying high off-state drain voltages in the order of several 100 V. In on-state, the buffer remains charged for some time, and the transistor channel electron concentration is reduced. The substrate potential strongly determines the electric field distribution inside the GaN buffer layers and may have impact on the magnitude of the dynamic R_{ON}.

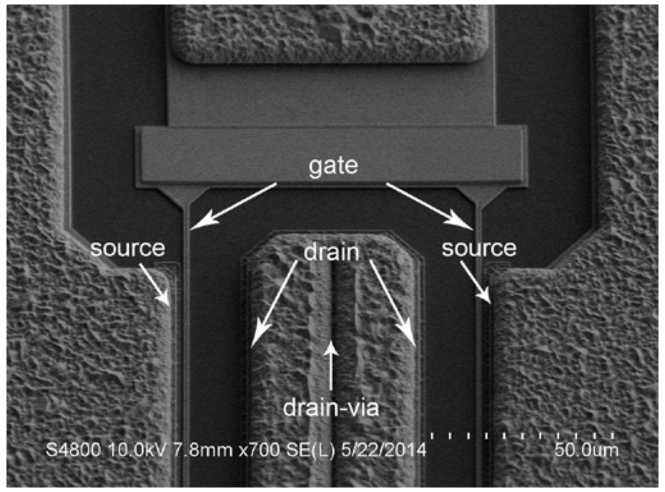


Fig. 2. SEM micrograph of a GaN HFET with the drain potential connected to the back side, the via trench inside the drain finger is visible.

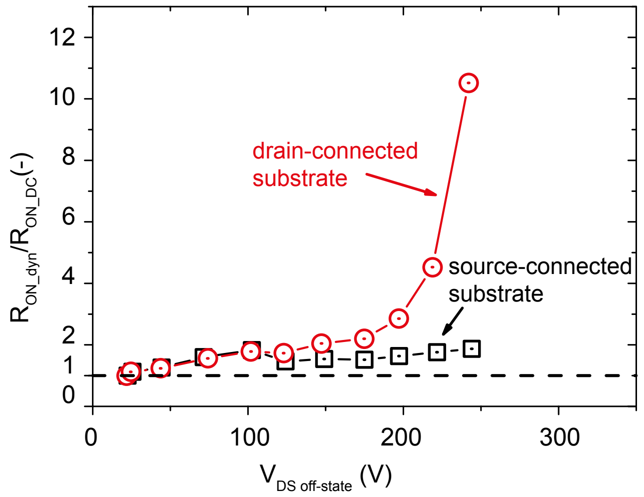


Fig. 3: Relative dynamic on-state resistance extracted from switching transients as function of the blocking voltage for quasi-vertical devices.

Source-down connected devices show a moderate dynamic R_{ON} increase by a factor of 1.9 for 250 V switching. In contrast, drain-down connected devices exhibit a much higher dynamic R_{ON} increase with a factor of 10.5. Root cause is the high electric field beneath the GaN-channel for the drain-down connected transistor at off-state conditions.

On-chip integration is a must for proper gate control and sufficiently low inductances at the targeted high converter switching-frequencies around 1 MHz. The quasi-vertical device architecture has proven to be a suitable technological approach for integration.

GaN-basierte Schalttransistoren für leistungselektronische Anwendungen sind intrinsisch lateral aufgebaut; Source und Drain befinden sich auf der Chipoberfläche. Das FBH hat ein neues quasi-vertikales Herstellungskonzept für derartige GaN-HFETs entwickelt. Es erlaubt – ähnlich wie bei etablierten und intrinsisch vertikal aufgebauten Si-basierten Superjunction MOSFETs – ein vertikales Anschlussschema der GaN-Chips. Dabei werden die Schwächen des lateralen Transistorkonzepts (höherer Halbleiterflächenverbrauch) eliminiert, dessen Stärken (Chipintegration von mehreren Transistoren und Dioden) aber beibehalten. Durch Gräben, die in die GaN-Halbleiterschichten geätzt werden, können wahlweise die Source- oder die Drainfinger der Transistorzellen mit dem leitfähigen Siliziumsubstrat und damit mit der Chipunterseite verbunden werden. Mit den so aufgebauten Transistoren – entweder mit Sourcepotenzial oder (hoher) Drainspannung an der Unterseite – kann die Erhöhung des dynamischen Einschaltwiderstands (R_{ON}) vertieft untersucht werden. Beim Schalten mit 250 V ist der dynamische R_{ON} für das sourceverbundene Si-Substrat um den Faktor 1,9 erhöht, für das drainverbundene Substrat um den Faktor 10,5.

Publication

P. Kotara, W. John, D. Stoppel, P. Wolter, L. Schellhase, S. Freyer, R. Zhytnytska, R. Lossy, O. Hilt, J. Würfl, G. Tränkle, "Source or drain down quasi-vertical GaN-on-Si HEMTs", Proc. 42nd Int. Symp. on Compound Semiconductors (ISCS), 28.6-2.7, Santa Barbara, USA (2015).

Highly efficient 2.4 kW interleaved buck converter with normally-off GaN HFETs

The semiconductor material gallium nitride (GaN) features unique material and electronic properties. In order to fully exploit the possibilities offered by the material itself, GaN power device technology, system relevant device characterization, and modelling techniques as well as electronic circuits adapted to the specific needs of GaN devices need to be interlinked. The Joint Lab Power Electronics, a cooperative activity of Technische Universität Berlin and the Ferdinand-Braun-Institut, is fully committed to this target. It brings together the respective strengths and know-how in power electronics available at both institutions and focusses on innovative solutions for electronic power converters by aligning device technology, circuit development, and packaging.

The activities focus to 75 mΩ normally-off GaN devices processed at FBH. Assembled into low-inductance microwave type packages, the devices are qualified and iteratively optimized for applications in high-power electronic energy converters. This encompasses model developments that take into account dynamic switching effects, the set-up of high-voltage and high-power pulsed measurement systems for device characterization at current levels exceeding 100 A and voltages up to 1000 V, as well as various test circuits to check the dynamic device response in dependence on different operation conditions. To efficiently benefit from GaN device performance in kilowatt-type power conversion systems, versatile Field Programmable Gate Array (FPGA)-controlled high-speed driver systems were additionally built up and put into operation.

A power switching system based on an interleaved buck converter topology (Figs. 1 and 2) was designed and successfully put into operation for demonstration and benchmarking purposes. As shown in Fig. 1, it consists of two power switching branches operating in anti-phase mode. During off-times of the transistors Q1 and Q2, the current stored in the inductors L1 and L2 commutes through the diodes D1 and D2. The phase shift of the currents in the two branches results in a low ripple output current, being additionally smoothened by the output capacitor. The measured waveforms given in Fig. 3 demonstrate the interplay between the two interleaving branches and visualize the current and voltage stress of the transistor Q1.

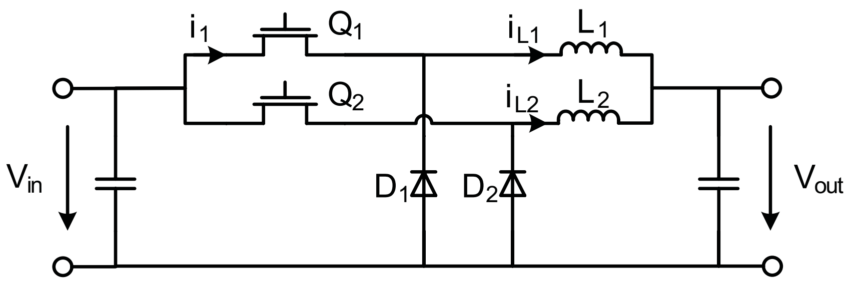


Fig. 1. Principal circuitry of interleaved buck converter.

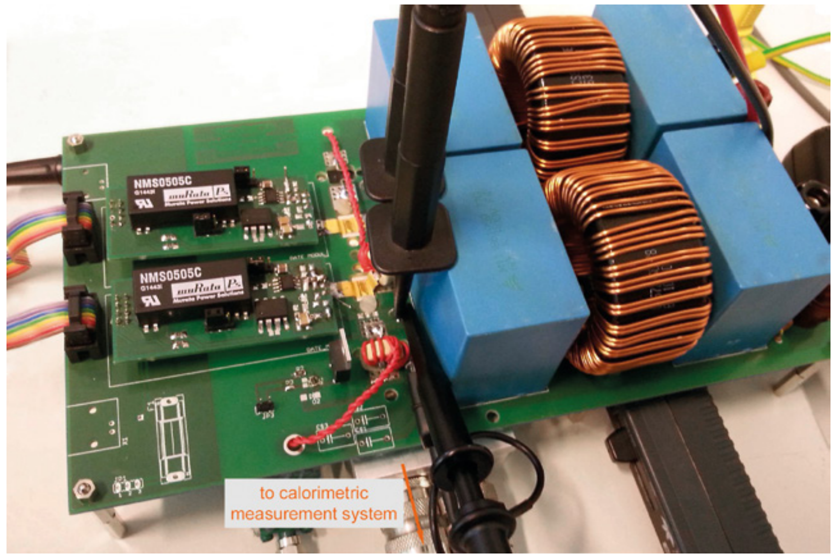


Fig. 2. Practical implementation of interleaved buck converter with driver stages (left), GaN power transistors and diodes (center), inductors and capacitors (right).

Power conversion efficiency is the most important selling argument for a given technology. A lot of effort has therefore been put into a calorimetric method of quantitatively measure conversion losses. For the interleaved buck converter, a specially designed heat sink filled with a liquid coolant connects to the switching transistors and the free-wheeling diodes (see Fig. 2). In continuous operation the devices are cooled with a constant flow rate of water. The dissipated losses are calculated from the coolant temperature and its volume flow rate. Using separate heat sinks additionally allows an individual loss determination of different heat sources. Furthermore, by taking into account the electrical power of the whole switching system, the losses of the remaining components can be monitored. Using this technique, the loss distribution between the GaN devices and the filter components can be investigated and optimized. The conversion efficiency of the interleaved buck converter according to Fig. 2 could be determined to 97.8 % for 200 V switching at a switching frequency of 200 kHz and a power level of 2.4 kW.

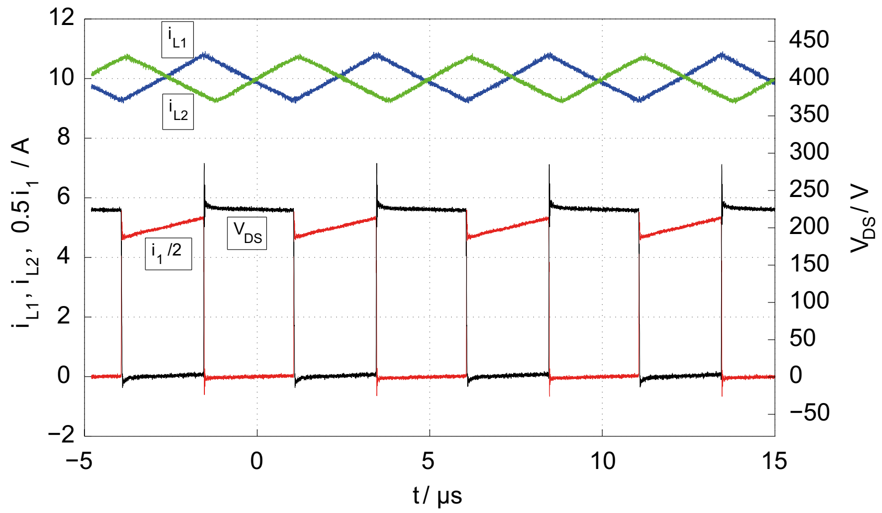


Fig. 3. Wave forms at 200 kHz as measured in the demonstrator circuit: i_{L1} and i_{L2} – current through the inductors L1 and L2, V_{DS} – drain-source voltage of transistor Q1, i_1 – current through transistor Q1.

Recent developments of the Joint Lab are aiming to achieve a higher voltage level, more output power, and an increased power density of GaN-based DC/DC converters. For further evaluations of the GaN devices it is crucial to have a benchmarking against other devices. However, different housings prevent investigations in the same set-up. Hence, two converters are built up that are completely identical except for the switching devices.

Furthermore, the converters have to be investigated regarding Electro Magnetic Compatibility (EMC) requirements. In order to achieve a better EMC, the layout of the power loop will be optimized using the developed simulation models.

Galliumnitrid-Halbleiter bieten einige herausragende Eigenschaften, die sich ideal für die Leistungselektronik eignen. Dank sehr schneller Schaltvorgänge bei gleichzeitig ausgezeichneten Leiteigenschaften sind überaus kompakte und hocheffiziente Umrichter möglich. Um das Potenzial in der Leistungselektronik auszuschöpfen, müssen die Halbleiterbauelemente im engen Zusammenspiel mit den leistungselektronischen Anforderungen entwickelt werden. Im Joint Lab Power Electronics bündeln das FBH und die TU Berlin ihre Erfahrungen in den Bereichen Bauelementtechnologie, Aufbautechnik, Ansteuer- und Schaltungstechnik sowie Hochfrequenztechnik. In diesem Rahmen wurde 2015 ein Gleichspannungswandler mit GaN-Leistungstransistoren des FBH entwickelt und aufgebaut. Dieser Umrichter arbeitet mit einer Schaltfrequenz von 200 kHz und erreicht bei einer Ausgangsleistung von 2,4 kW und einer Ausgangsspannung von 200 V einen Wirkungsgrad von 97,8 %. Ein speziell entwickeltes kalorimetrisches Messsystem ermöglicht eine detaillierte Analyse der Transistorverluste in Abhängigkeit von Betriebspunkt und Schaltfrequenz.

Publications

O. Hilt, R. Zhytnytska, J. Böcker , E. Bahat-Treidel, F. Brunner, A. Knauer, S. Dieckerhoff, J. Würfl, "70 mΩ/600 V normally-off GaN transistors on SiC and Si substrates", IEEE 27th International Symposium on Power Semiconductor Devices & IC's (ISPSD), Hong Kong, pp. 237-240 (2015).

J. Böcker, H. Just, O. Hilt, N. Badawi, J. Würfl, S. Dieckerhoff, "Experimental analysis and modeling of GaN normally-off HFETs with trapping effects", 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), Geneva, pp. 1-10 (2015).

N. Badawi, O. Hilt, E. Bahat-Treidel, J. Böcker, J. Würfl, S. Dieckerhoff, "Investigation of the dynamic on-state resistance of 600V normally-off and normally-on GaN HEMTs", IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, pp. 913-919 (2015).

R. Zhytnytska, J. Böcker, H. Just, E. Bahat-Treidel, O. Hilt, S. Dieckerhoff, J. Würfl, G. Tränkle, "Thermal characterization of AlGaN/GaN HEMTs on Si and n-SiC substrates", Proceedings Int. Conf. on Compound Semiconductor Manufacturing Technology (CS ManTech), (2015).

J. Würfl, M. Troppenz, O. Hilt, E.Bahat-Treidel, N. Badawi, J. Böcker, S. Dieckerhoff, "Dynamics of drift effects in GaN power switching transistors", Wocsdice, Smolenice, invited lecture (2015).

J. Böcker, N. Badawi, O. Hilt, E. Bahat-Treidel, J. Würfl, S. Dieckerhoff, "Operation and dynamics of GaN normally-off devices in DC-DC converters", ETG Workshop, Nürnberg, invited lecture (2015).

For further information:

http://www.fbh-berlin.com/research/iii-v-electronics

III-V Technology

III/V-Technologie

III/V-Technologie

Im Forschungsbereich III/V-Technologie bündelt das FBH sein Know-how und seine Ressourcen in der Material- und Prozesstechnologie sowie in der Aufbau- und Verbindungstechnik. Diese bilden die Basis für die Entwicklung von Bauelementen in den Forschungsbereichen Photonik und III/V-Elektronik:

- ***Epitaxie Nitride*** – Heterostrukturen für UV-LEDs, UV-Fotodetektoren, violette Laserdioden und GaN-Transistoren. Diese Heterostrukturen sind die Basis für die Entwicklung der entsprechenden Bauelemente am FBH. Weiterhin wird an HVPE-Prozessen für GaN- und AlGaN-Substrate und -Templates geforscht.

- ***Epitaxie Arsenide*** – Heterostrukturen für GaAs-Laserdioden sowohl für die Bauelemententwicklung am FBH als auch für externe Kunden. Darüber hinaus werden SAM-Strukturen für gepulste Lasersysteme entwickelt.

- ***Prozesstechnologie*** – Prozesse für eine Vielzahl von GaAs-, InP- und GaN-Bauelementen auf Waferdurchmessern von 2" bis 4". Diese werden auf der industriekompatiblen und zugleich flexiblen Prozesslinie durchgeführt und beständig weiterentwickelt.

- ***InP Devices & SciFab*** – InP-HBTs für THz-Frequenzen, die die Basis für die THz-Systeme am FBH darstellen. Integriert mit Si-BiCMOS-Schaltkreisen wird diese Technologie in Kooperation mit dem Leibniz-Institut IHP auch für externe Kunden bereitgestellt.

- ***Aufbau- und Verbindungstechnik*** – die Bauelemente werden auf Wärmesenken oder in Gehäuse eingebaut und damit für den Aufbau von Modulen und Systemen nutzbar gemacht.

- ***Materialanalytik*** – unterstützt die Entwicklungen in der Epitaxie durch Charakterisierung der Eigenschaften der Halbeiterstrukturen. Diese Kompetenzen werden auch für die Entwicklung von Prozess- und Montageschritten sowie für die Analyse von Ausfallursachen der entwickelten Bauelemente eingesetzt.

Wir nutzen unsere technologische Infrastruktur auch für Aufträge von externen Partnern, indem wir z.B. Prozessmodule bereitstellen, Epitaxiestrukturen liefern oder Gerätedemonstratoren entwickeln und fertigen.

III-V Technology

The research area III-V technology combines know-how and resources at FBH in materials and process technology as well as mounting and packaging. These competencies form the basis for the development of devices in the photonics und III-V electronics research areas.

- ***Epitaxy nitrides*** – heterostructures for UV LEDs, UV photodetectors, violet laser diodes, and GaN transistors. These heterostructures are the basis for the respective devices at FBH. Additionally, HVPE growth processes for GaN and AlGaN substrates and templates are developed.

- ***Epitaxy arsenides*** – heterostructures for GaAs laser diodes for device development at FBH as well as for external customers. Also, SAM structures for pulsed laser systems are fabricated.

- ***Process technology*** – processes for a large variety of devices based on GaAs, InP, and GaN on wafers from 2" to 4" in diameter. These are carried out and continuously improved on a process line that is compatible with industry standards, offering high flexibility at the same time.

- ***InP devices & SciFab*** – InP HBTs for THz frequencies form the basis for FBH THz systems. Monolithically integrated with Si BiCMOS circuits, this technology is also made available to external customers in cooperation with the Leibniz institute IHP.

- ***Mounting & assembly*** – devices are mounted onto heat sinks or into packages to allow for integration into modules and systems.

- ***Materials analytics*** – supports the development of epitaxial growth processes by characterization of heterostructures. These analysis techniques are also utilized for the development of processing and mounting steps as well as for the analysis of root causes for device failure.

We also make our technological infrastructure available to external partners, for whom we carry out process modules, deliver epitaxial wafers or develop and build demonstrator systems.

InP DHBT integrated circuit technology for applications in the mm-wave region and beyond

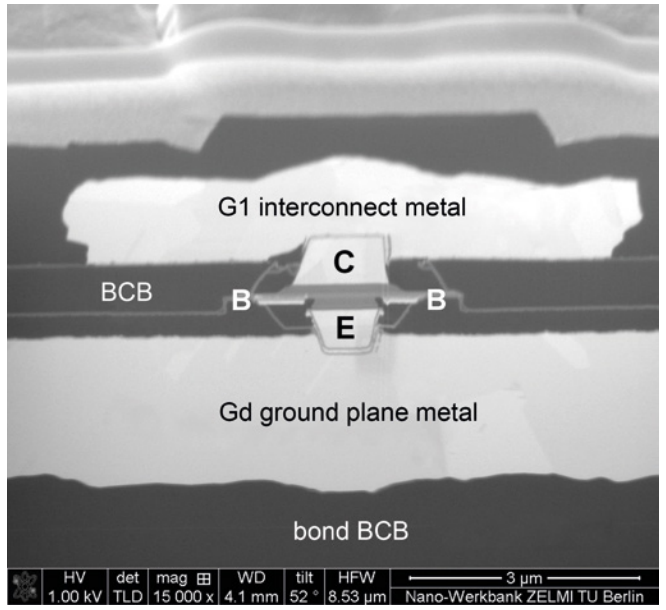


Fig. 1. Focused ion beam cross-section of heterointegrated 800 nm emitter width InP DHBT.

The electromagnetic spectrum between 300 and 1000 GHz is currently underused for the lack of suitable integrated electronic components. Electronic circuits in this frequency band for signal generation, amplification and other analog functions such as frequency multiplication are best made from indium phosphide (InP) and related materials. This is due to the unique combination of high electric breakdown field and fast electron transport in these materials. FBH has developed a monolithically integrated circuit technology built around high-frequency and high-power InP bipolar transistors, with circuit operating frequencies between 100 and 350 GHz. The InP double heterostructure bipolar transistors (DHBTs) at the core of this technology are fabricated in a transferred substrate approach. A cross-section of an HBT device with 800 nm wide emitter is shown in Fig. 1. The transferred substrate technology enables the reduction of parasitic feedback capacitances by separate top and bottom device structuring and offers an optimized microstrip topology by placing the active device between the RF ground plane and the microstrip signal line.

A key characteristic of FBH's transferred substrate InP DHBT technology is that it can be expanded and integrated with other environments in a modular fashion, since in the process the active and passive elements are removed from the native InP substrate. Most notably is the monolithic InP DHBT integration with fully processed SiGe BiCMOS wafers, leading to a completely interwoven layer stack. The tight spatial integration eliminates costly high-frequency packaging and allows the realization of mm-wave RF front ends in a very small form factor. Within the three-year Leibniz project *SciFab*, a complete process design kit (Fig. 2) which includes all BiCMOS and InP layers and device structures was released to external users [1]. The performance of recently realized heterointegrated circuits is detailed on page 90.

For THz applications, the InP DHBTs cutoff frequency can be increased by geometrical scaling, i.e., commensurate shrinking of the junction areas along with reduced vertical device layer thickness. A first attempt of reducing the emitter width from 800 to 500 nm resulted in an improvement of the HBT's f_{max} from 350 to more than 450 GHz. Cascode gain stages realized with the new device geometry showed improved gain and bandwidth over the baseline technology.

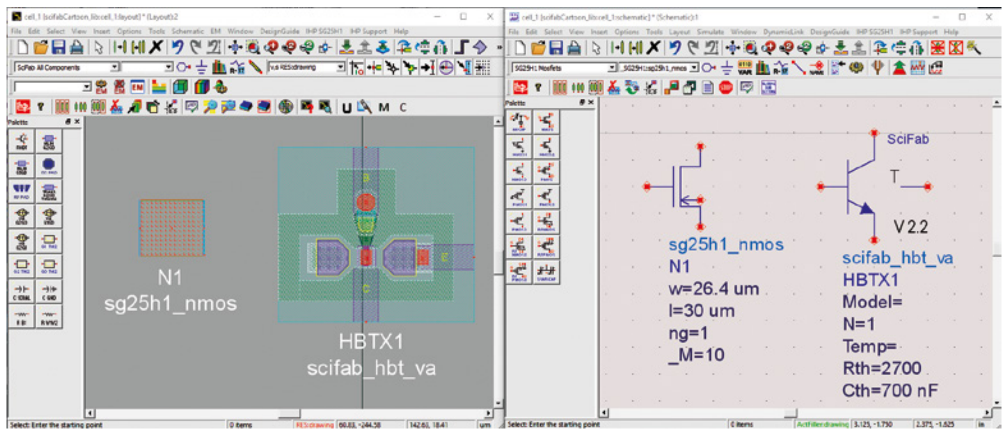


Fig. 2. Screenshot of BiCMOS and InP HBT layout and corresponding schematic, highlighting the seamless co-design capability built into the FBH/IHP "SciFab" process design kit.

In the transferred substrate InP DHBT topology, the heat generated in the transistor can only be extracted through the emitter and collector contact metal patches, since the connection to the substrate body is removed in the process. Within the three-year BMBF VIP project *AVTE*, FBH expanded the technology by modularly integrating a thin-film diamond heat spreading layer into the InP DHBT transferred substrate technology [4]. In 2015, circuit wafers with diamond heat spreading layer were completed. A processed wafer is shown in Fig. 3. Wideband amplifiers realized in this technology demonstrated improved power output (> 200 mW) and improved power-added efficiencies of 15 % at W-band. The transistor's thermal resistance could be reduced to below 0.7 K/mW, an improvement of more than a factor of three and a record number for submicrometer InP DHBTs [2].

Multichip modules operating at THz frequencies were realized with $Au_{80}Sn_{20}$ bump flip-chip assembly, including passive and active sub-THz chips mounted onto engineered multilayer substrates. Stripline geometries were realized in a three-layer BCB/gold integration with 10 µm lateral design rule. The vertical flip-chip transition between carrier substrate and THz chip was designed to resemble a coaxial vertical waveguide by ground shielding the transition area with multiple bumps arranged in a circular pattern around the signal contact. A record bandwidth of more than 320 GHz was measured for passive flip-chip assemblies [3]

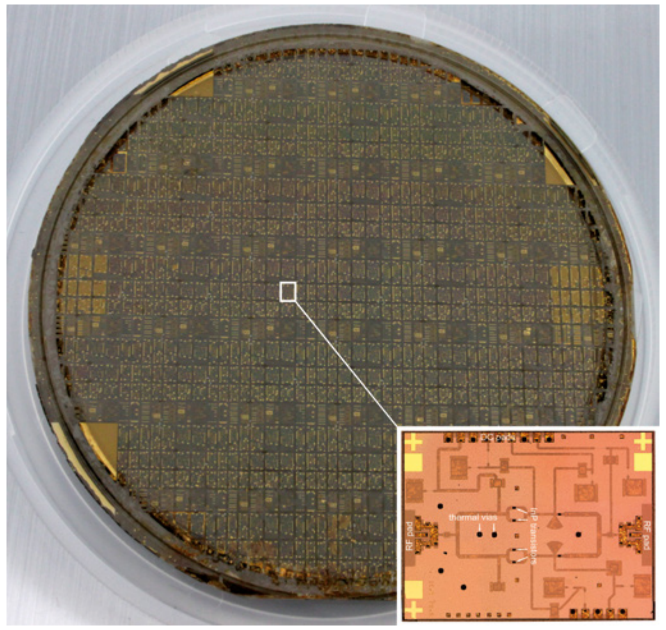


Fig. 3. InP DHBT mm-wave circuit wafer (75 mm diameter) with monolithically integrated diamond heat spreading layer. Inset shows microphotograph of power amplifier circuit (0.8 x 1.2 mm²).

Das FBH entwickelt seine InP-HBT-Technologie für Höchstfrequenzanwendungen über 100 GHz stetig weiter. Aktuell werden höhere Transistor-Grenzfrequenzen jenseits von 400 GHz erschlossen mithilfe geometrischer Skalierung, Optimierung der ohmschen Kontakte sowie Anpassung der epitaktischen Heterostruktur. Weltbeste thermische Bauelementwiderstände um 0,7 K/mW konnten mit einer Wafer-gebondeten nanokristallinen Diamant-Wärmeableitschicht erreicht werden. Diese ermöglicht höhere Leistungsdichten im mm-Wellen-Band und darüber und ist mit der InP-HBT-Schaltkreisumgebung voll kompatibel. Die damit realisierten Leistungsverstärker zeigen eine doppelt so hohe Ausgangsleistung bei 90 GHz verglichen mit der Basistechnologie. Externen Kunden stellt das FBH seine InP-HBT-Technologie in einer monolithisch CMOS-integrierten Variante in Zusammenarbeit mit dem Leibniz-Institut für innovative Mikroelektronik (IHP) im Foundry Modus zur Verfügung. Die hierzu notwendige Design- und Prozessbibliothek (Process Design Kit) beinhaltet alle Strukturen und Ebenen der InP-HBT- sowie der SiGe-BiCMOS-Technologie und ermöglicht ein komplettes Co-Design von heterogen-integrierten InP/Silizium-Höchstfrequenzschaltkreisen.

Publications

[1] N.G. Weimann, D. Stoppel, M.I. Schukfeh, M. Hossain, T. Al-Sawaf, B. Janke, R. Doerner, S. Sinha, F.-J. Schmückle, O. Krüger, V. Krozer, W. Heinrich, M. Lisker, A. Krüger, A. Datsuk, C. Meliani, B. Tillack, "SciFab – a wafer-level heterointegrated InP DHBT/SiGe BiCMOS foundry process for mm-wave applications", phys. stat. sol. (a), doi: 10.1002/pssa.201532549 (2016).

[2] K. Nosaeva, T. Al-Sawaf, W. John, D. Stoppel, M. Rudolph, F. J. Schmückle, B. Janke, O. Krüger, V. Krozer, W. Heinrich, and N. G. Weimann, "Multifinger Indium Phosphide Double-Heterostructure Transistor Circuit Technology With Integrated Diamond Heat Sink Layer", IEEE Transactions on Electron Devices, vol. PP, no. 99, pp. 1–7 (2016).

[3] S. Monayakul, S. Sinha, F.J. Schmückle, M. Hrobak, D. Stoppel, O. Krüger, B. Janke, N.G. Weimann, "Process robustness and reproducibility of sub-mm wave flip-chip interconnect assembly", Electrical Performance of Electronic Packaging and Systems (EPEPS), 2015 IEEE 24th, pp. 141–144 (2015).

[4] K. Nosaeva, N. Weimann, M. Rudolph, W. John, O. Krüger, W. Heinrich, "Improved thermal management of InP transistors in transferred-substrate technology with diamond heat-spreading layer", Electron. Lett., vol. 51, no. 13, pp. 1010-1012 (2015).

Laser diodes emitting at 1180 nm for frequency-converted yellow lasers

Laser diodes emitting in the yellow-green range are key components for many applications. Unfortunately, this spectral region is currently not accessible directly with laser diodes. Non-linear frequency conversion can close this gap, but requires high-brilliance laser diodes emitting in the spectral range between 1100 nm and 1200 nm. When using $In_xGa_{1-x}As$ quantum wells (QW) crystal growth has to be optimized to cope with the high strain to the GaAs substrate. For emission wavelengths beyond 1100 nm, single QWs approach the theoretical critical thickness for the formation of dislocation lines according to Matthews-Blakeslee's model and multi quantum wells clearly exceed this limit. Since such dislocations lead to rapid degradation of laser diodes it is necessary to optimize the growth process and the design of the laser structures in order to accommodate the high strain without defect formation.

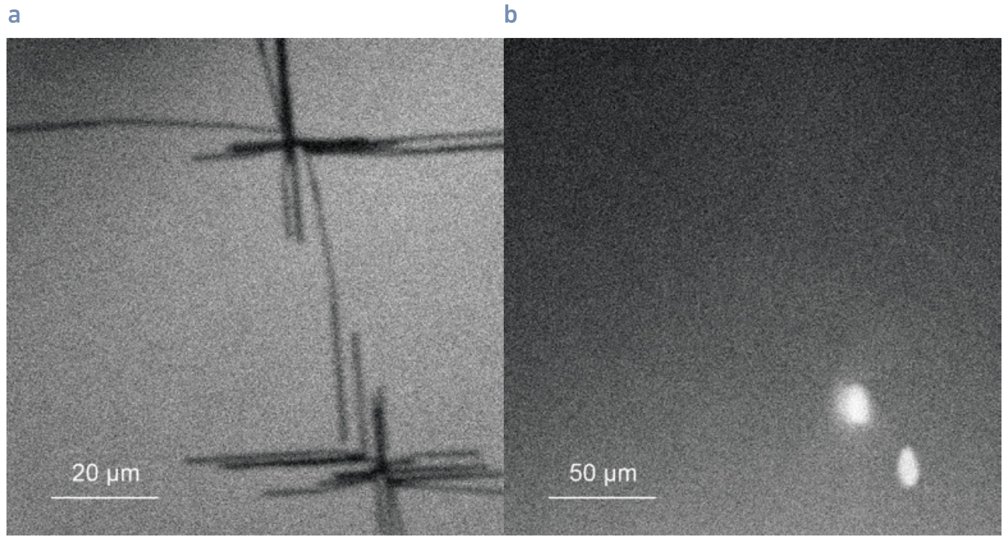


Fig. 1. CL images of 1180 nm laser structures with 6 nm $In_{0.39}Ga_{0.61}As$ QW without GaAsP barriers (a), embedded in 7 nm $GaAs_{0.8}P_{0.2}$ barriers (b).

The corresponding layer structures were grown at FBH by metal organic vapor phase epitaxy (MOVPE) in an Aix 200/4 reactor and analyzed by high-resolution X-ray diffraction, photoluminescence (PL) at room temperature, and cathodoluminescence (CL) at 80 K. To characterize the properties of such laser structures they were processed into broad area (BA) laser diodes with 100 µm stripe width and different cavity lengths between 0.4 mm and 4 mm.

Yellow-orange emission at 590 nm requires an infrared laser source emitting at 1180 nm with a very high indium content in excess of 30 % in the $In_xGa_{1-x}As$ QW. Different QW configurations were investigated for this wavelength. The first option, a 6 nm thick InGaAs QW with a PL wavelength of 1173 nm embedded in GaAs shows crossed dark line defects in the QW (Fig. 1a) and is thus not suited. Embedding this QW in 7 nm $GaAs_{0.8}P_{0.8}$ barrier layers, the formation of defects can be suppressed (Fig. 1b) by partial (≈ 60 %) strain compensation. However, the increased barrier height leads to a blue shift to 1158 nm.

Two different quantum wells with different thicknesses (6 and 9 nm) and indium contents (39 % and 36.5 %), both with an emission wavelength of 1182 nm and GaAsP strain compensating barriers, were tested as BA laser diodes. The thicker QW contains less indium for the desired emission wavelength. Nevertheless, the product of strain time quantum well thickness is higher in this case and therefore the strain compensation by the $GaAs_{0.8}P_{0.2}$ barriers is lower.

An asymmetric laser structure with a lower p-side thickness was chosen to achieve lower series resistance and better heat dissipation in p-down mounting. The structure contains a 2.1 µm thick $Al_{0.25}Ga_{0.75}As$ n-cladding layer, an active region embedded in 100 nm thick GaAs waveguide layers grown at 520°C, a 1.3 µm p-doped $Al_{0.25}Ga_{0.75}As$ cladding layer grown at 760°C, and a 100 nm p^{++}-doped GaAs contact layer (Fig. 2). The high indium content in the QW requires low growth temperature to suppress indium segregation. The lower affinity of GaAs to oxygen and point defect incorporation in comparison to AlGaAs allows for growth of the waveguide at the same low growth temperature and avoids growth interruption close to the QW.

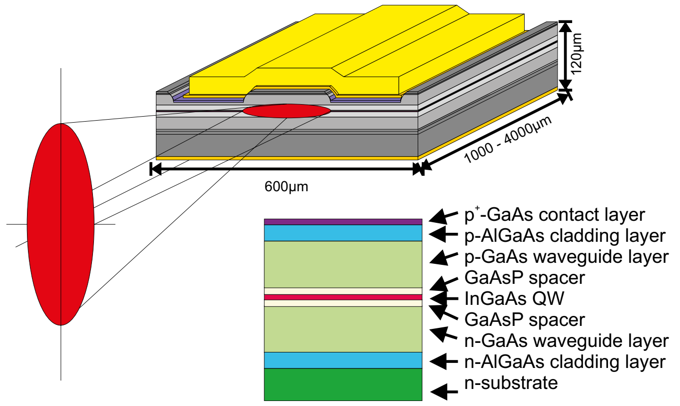


Fig. 2. Schematic of the broad area laser structure.

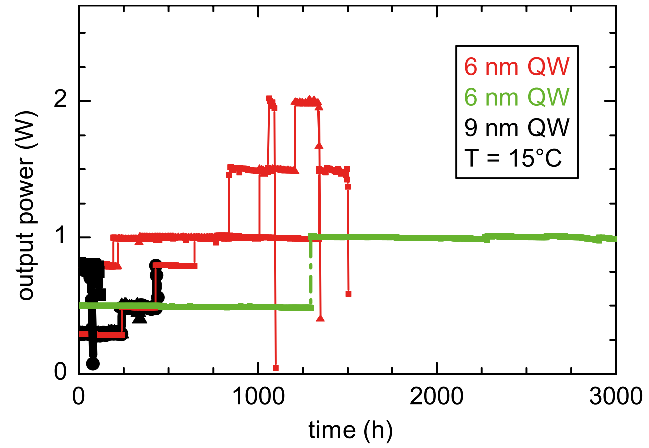


Fig. 3. Step stress-test for BA laser diodes emitting at 1180 nm.

Additionally, the higher thermal and electrical conductivity of GaAs waveguide layers reduce resistive heating and facilitate the removal of heat from the active region.

The threshold current density and slope efficiency of these BA laser diodes are quite similar (115 A/cm², 0.282 A/W for the 6 nm QW and 109 A/cm², 0.275 A/W for the 9 nm QW), and also the output power of 1.5 W in CW mode at 3 A is comparable in both cases.

Both structures were subjected to a step-stress test increasing the output power by 0.5 W in intervals of several hundred hours. Fig. 3 shows a dramatic difference between these laser diodes. The structure with a 9 nm QW failed at an output power of 0.75 W by formation of dark line defects. In contrast, the structure with a 6 nm QW survived at 1.5 W for more than 1,000 h and failed only at an output power of 2 W. At 1 W lifetimes > 3,000 h were obtained. This shows the necessity of careful optimization of layer structure and growth process for such highly strained devices. To the best of our knowledge these are the first laser diodes at 1180 nm emission wavelength showing sufficient stability for long-term operation at high output powers. More application-oriented details can be found on p. 70.

This work is supported within the InnoProfile Transfer initiative *YELLOW* by the Federal Ministry of Education and Research (BMBF) under contract 03IPT613Y.

Der gelb-grüne Spektralbereich ist derzeit mit Laserdioden nicht direkt zugänglich. Jedoch ermöglicht die Frequenzkonversion von Laserdioden mit einer Emission im Bereich von 1100 nm bis 1200 nm kompakte Laserquellen in diesem Wellenlängenbereich und erschließt damit interessante Anwendungen. Für diese sehr langwellige Emission werden Laserdioden mit sehr hoch verspannten $In_xGa_{1-x}As$-Quantentrögen (x > 0,3) benötigt. Jedoch neigen diese zur Bildung von Versetzungen und degradieren entsprechend schnell. Spannungskompensierende $GaAs_yP_{1-y}$-Schichten können jedoch diese Versetzungsbildung verhindern. Weiterhin ist die Wahl des Quantentrogs entscheidend. Die angestrebte Wellenlänge von 1180 nm lässt sich mit 6 nm Dicke und hohem Indium (In)-Gehalt (39 %) oder mit 9 nm Dicke und reduziertem In-Gehalt (36,5 %) erreichen. Während sich Schwellenstromdichte und Effizienz nicht wesentlich unterscheiden, zeigen nur die 6 nm dünnen Quantentröge ausreichende Lebensdauern von > 3.000 h bei 1 W Ausgangsleistung. Damit stehen erstmalig ausreichend stabile Laserdioden für Laserquellen im gelben Spektralbereich zur Verfügung.

Publications

K. Paschke, F. Bugge, G. Blume, D. Feise, G. Erbert, "High-power diode lasers at 1178 nm with high beam quality and narrow spectra", Optics Letters, vol. 40, no. 1, pp.100-102 (2015).

F. Bugge, K. Paschke, G. Blume, D. Feise, U. Zeimer, M. Weyers, "Growth of laser diode structures with emission wavelength beyond 1100 nm for yellow-green emission by frequency conversion", J. Crystal Growth, vol. 414, pp. 205-209, (2015).

Carbon tetrabromide-based in situ etching of GaAs improved by TMAl

Buried structures produced in multiple growth steps can enhance the functionality of laser diodes. Passive sections, for example, can be used for phase modulation, beam shaping, and reduction of leakage currents. Conventional ex situ patterning for AlGaAs results in an oxide layer that disturbs or even inhibits subsequent regrowth. A combination of pattern generation and regrowth by metal organic vapor phase epitaxy (MOVPE) in the same reactor could avoid this oxide formation. Carbon tetrabromide (CBr_4) is widely used in MOVPE, also at FBH, to incorporate C as a p-dopant in GaAs and AlGaAs. Addition of CBr_4 during growth is also known to reduce the growth rate due to Br-related etching reactions. As such etching reactions could be useful for pattern transfer inside an MOVPE reactor they were studied at FBH.

a b

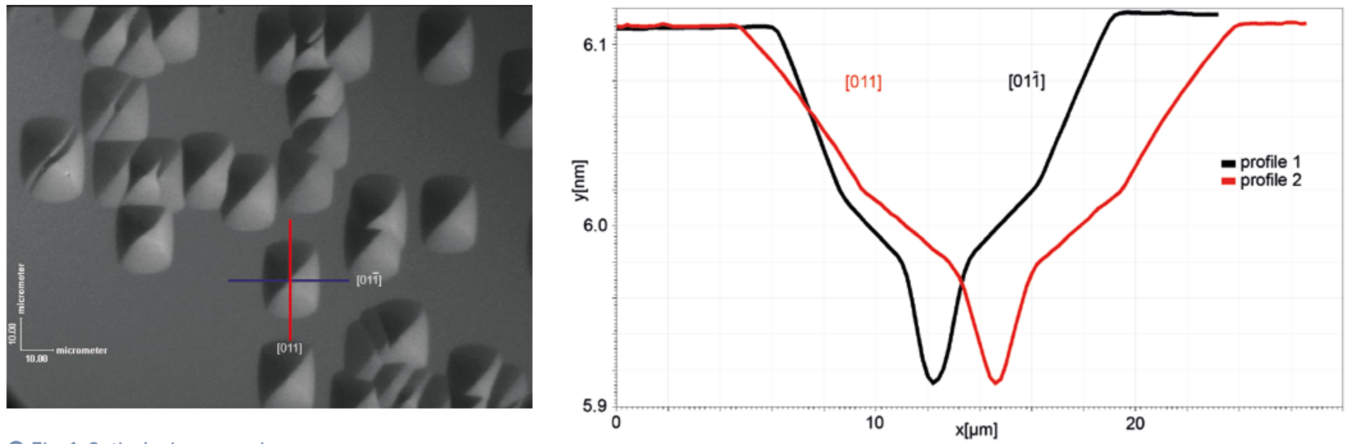


Fig. 1. Optical microscope image of etch pits (a) and AFM scans along perpendicular directions (b) of GaAs surface after CBr_4 etch.

The in situ etching experiments were carried out in a planetary MOVPE reactor (AIX2400G3) in the temperature range between 575°C and 675°C. The material to be etched was epitaxial GaAs previously grown on GaAs wafers. The atmosphere inside the reactor chamber was composed of the carrier gas (hydrogen), arsine (AsH_3) – which is needed to prevent surface´s degradation due to loss of Arsenic – and CBr_4. Trimethylaluminium (TMAl) and trimethylgallium (TMGa) have been added in moderate quantity during the in situ etch to study the effect of additional reaction pathways. Optical microscopy, scanning electron microscopy (SEM), cathodoluminescence (CL), and atomic force microscopy (AFM) were employed to characterize the samples.

Etching of about 150 nm of GaAs with CBr_4 leads to the formation of etch pits on the surface (Fig. 1a); AFM scans proved them to be pits with a depth of about 200 nm (Fig. 1b). Changing the temperature did not have a significant impact on their shape, size, and number. Cathodoluminescence (CL) images show dark spots in the center of such pits, indicating that they are seeded by dislocations present in the substrate or in the etched epitaxial layer structure (Fig. 2).

a b

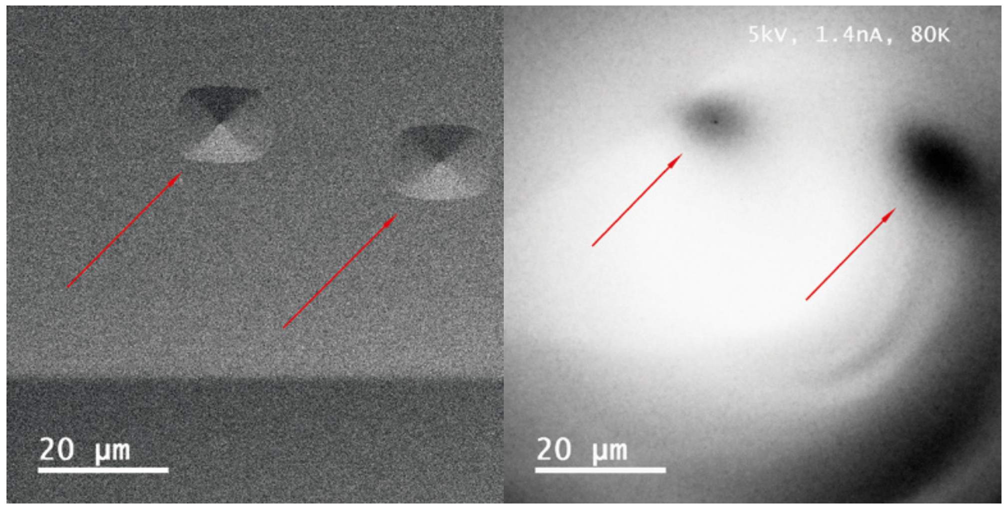


Fig. 2. SEM image with secondary electrons (a) and panchromatic CL image (b) of same area of a GaAs surface etched only with CBr_4 at 575°C recorded at 80 K.

a b

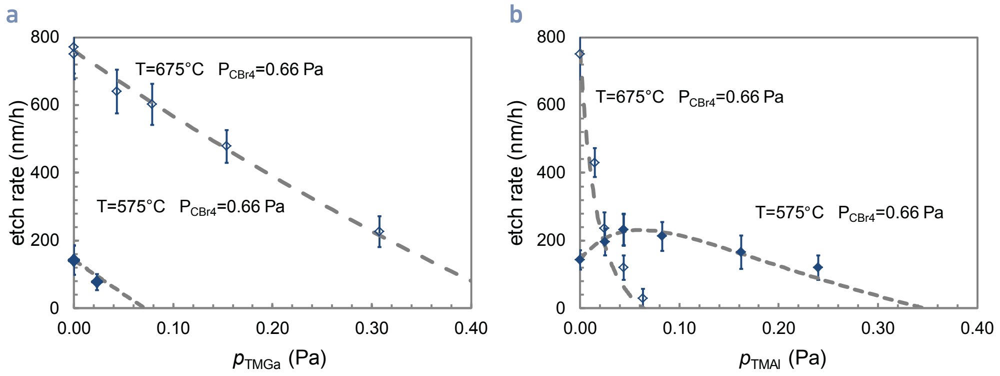


Fig. 3. Experimental values for GaAs etch rate with addition of (a) TMGa and (b) TMAl at 675°C (empty) and 575°C (filled).

a b

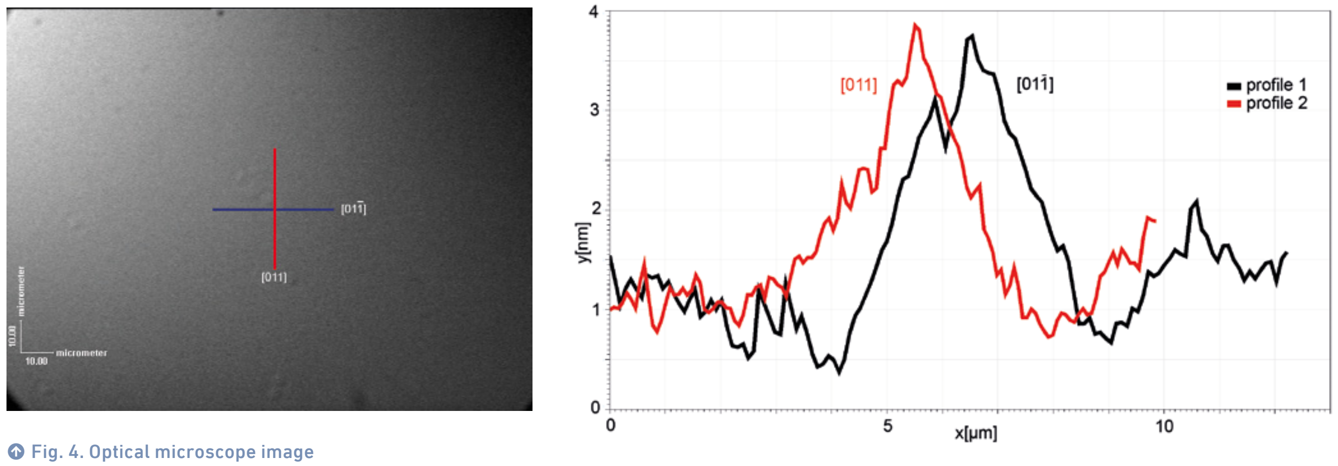


Fig. 4. Optical microscope image of shallow hillocks (a) and AFM scans along perpendicular directions (b) of GaAs surface after CBr_4 etch with addition of TMAl.

Adding TMGa during the etching of GaAs with CBr_4 reduces the etch rate due to competition with growth (Fig. 3a). Both processes growth and etching are apparently independent. Thus, the etch rate can be simply interpreted as the etch rate in presence of CBr_4 (and in absence of TMGa) minus the growth rate in presence of TMGa (and in absence of CBr_4). The development of etch pits is unaffected by the presence of TMGa.

However, adding TMAl during etching has a much more complex effect: the etch rate at high temperatures is strongly reduced, probably due to a "masking" by AlAs forming on the surface, while the etch rate at low temperatures is enhanced (Fig. 3b).

TMAl not only affects the etching reaction, but also prevents the formation of unwanted etch pits; only very shallow hillocks mark the position of the dislocations (Fig. 4). A possible explanation of this effect lies again in the formation of a passivation layer of AlAs, which could slow down the etching especially at dislocations. These results suggest that TMAl-assisted CBr_4 etching could be a useful tool for MOVPE in situ pattern transfer into AlGaAs structures without contact to oxygen.

Vergrabene Strukturen können die Funktionalität von Laserdioden erhöhen, etwa durch passive Bereiche zur Phasenmodulation. Diese lassen sich jedoch aufgrund der hohen Oxidationsneigung bei AlGaAs-basierten Strukturen nur schwer realisieren. Strukturübertragung direkt im MOVPE-Reaktor mittels CBr_4, das bereits als p-Dotierquelle genutzt wird, kann diese Hürde beseitigen. Die Gasphasenätzung von GaAs in einem MOVPE-Reaktor ist möglich, um AlGaAs-Heterostrukturen mittels CBr_4 zu produzieren. Allerdings greift dieses Verfahren insbesondere an Versetzungen an und erzeugt Ätzgruben. Dies lässt sich aber mit der Zugabe geringer Mengen von TMAl verhindern. Darüber hinaus erhöht TMAl bei niedrigen Temperaturen die Ätzrate. Daher ist die Gasphasenätzung mit CBr_4, die durch TMAl unterstützt wird, ein vielversprechender Prozess zur Realisierung vergrabener AlGaAs-Strukturen mit hoher struktureller Perfektion und minimiertem Sauerstoffeinbau.

Publication

P. Della Casa, A. Maaßdorf, U. Zeimer, M. Weyers, "CBr_4-based in-situ etching of GaAs, assisted with TMAl and TMGa", J. Crystal Growth 434, pp. 116-122 (2016)

III-V Technology III/V-Technologie

Hydride vapor-phase epitaxy for semi-insulating GaN substrates

Gallium nitride (GaN) is a compound semiconductor that serves as the base for modern applications in solid-state lighting, data storage, power handling, and communication electronics. Unlike in case of silicon and gallium arsenide, which are the basis for established mass products, GaN substrates cannot be synthesized from melt. However, the growth of device structures on foreign substrates like sapphire or silicon carbide (SiC) is often only second choice and does not allow for taking full benefit of the inherent material properties of group-III nitrides. Fabrication of GaN substrates is difficult, and the most successful technique in this field so far is hydride vapor-phase epitaxy (HVPE). Very high growth rates, highest material purity, and favorable electrical and thermal properties have been demonstrated [3]. N-type conductivity of GaN substrates is achieved by doping with silicon [2], which is required for laser diodes and ultra-high brightness light-emitting diodes and, with lower electron densities, also for vertical high-power switches. Semi-insulating properties of GaN substrates required to substitute SiC substrates in high-power high-frequency communications with long operation reliability can be achieved by iron doping.

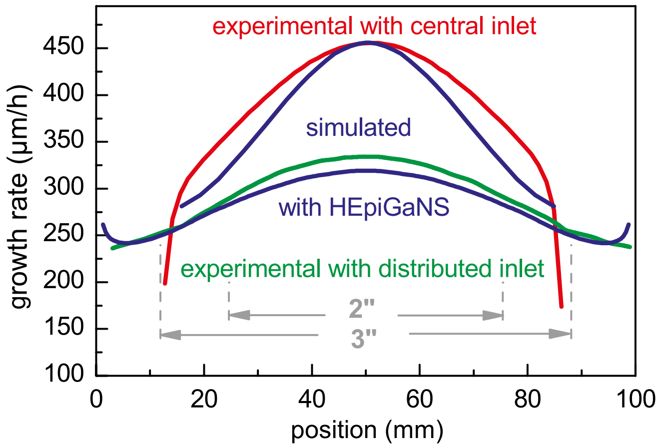


Fig. 1. Growth rate distributions and uniformities calculated by simulation (black) and measured for GaN layer growth under optimized conditions for minimum strain incorporation for the original central gas inlet (red) and developed distributed gas inlet (blue) with much higher uniformity across the wafer.

The FBH, in close cooperation with industrial and academic partners, conducts the corresponding research on GaN HVPE by developing a targeted process for mm-thick, semi-insulating GaN crystals with up to 4 inch in diameter. To this end, the substrate diameter in an industry-like vertical AIX-HVPE reactor was successively enlarged from 2 inch to 4 inch, and doping with iron using the metal-organic doping source ferrocen was introduced.

The increase of the wafer diameter comprised proper changes in the interior reactor design and process parameters. Sapphire substrates were used because of their availability. Substrate holders for 3 and 4 inch substrates were constructed, which allowed for safe face-down mounting without growth on the wafer edges. The incoming gases, i.e., nitrogen, hydrogen, hydrochloric acid gas which reacts with gallium to gallium chloride gas, and ammonia have to be introduced into the reactor by gas inlets in a way that they are uniformly distributed across the wafer surface. Obviously, gases can be much more concentrated into the center of a 2 inch substrate than in the case of a 4 inch substrate. Thus, new inlets had to be constructed. Growth procedures for a high, uniform growth rate over the entire wafer area with proper gas mixture and, at the same time, negligible parasitic deposits at the reactor walls and inlet parts had to be developed. In addition to the properties of the substrate that were defined in a preceding MOVPE growth step, a so called GaN/sapphire template, the exact composition of the process gases, in particular the mixing ratio of hydrogen and nitrogen, also decides on the ability to grow thick layers. Improper mixtures lead to incorporation of large amounts of strain in the growing GaN layer and subsequent crack formation rendering the crystal useless. These challenges were tackled by combing simulation using the virtual reactor simulator HEpiGaNS (STR GmbH) with experimental validation. It was found that the growth of layers with thicknesses of 1 mm and more requires a fraction of 70 +/-5 % of hydrogen in our reactor with the distributed inlet geometry [1]. Linescans of the growth rates obtained from simulations and experiments are shown in Fig. 1 for the original central gas inlet and for the final distributed gas inlet. Although growth rates using a central gas inlet exceeded 300 µm/h, the uniformity of this configuration with 13 % for a 3 inch substrate surface hinders any size scaling. The process developments ended up with a uniformity of 9 % for 4 inch wafer size with an average growth rate of 280 µm/h. A map of the growth rate on a 4 inch substrate is shown in Fig. 2. Freestanding GaN crystals with a thickness of 3 mm have been demonstrated which show full width at half maxima in the x-ray rocking curves of 50 arcsec at (0002) reflection and of 60 arcsec at (30-32) reflection. The lattice bending radius was +3.3 m.

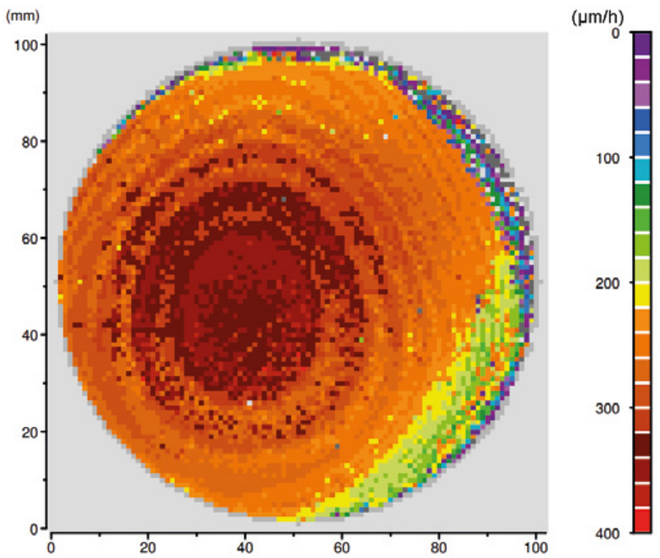


Fig. 2. Map of the growth rate of a GaN layer grown by vertical AIX-HVPE on a 4 inch GaN/sapphire template as shown in Fig. 1.

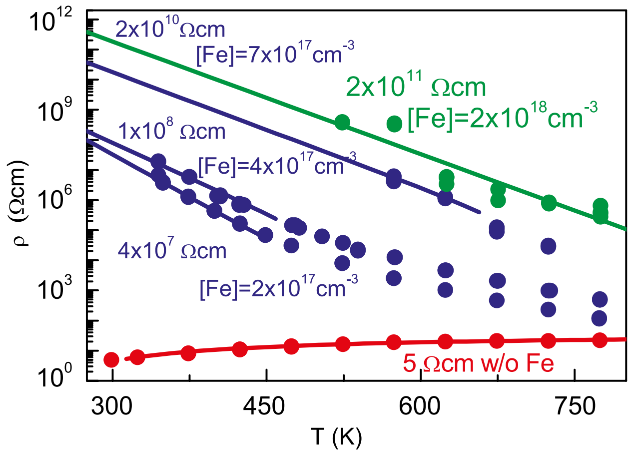


Fig. 3. Temperature dependency of specific resistivity of non-intentionally doped GaN (w/o Fe) and with iron-doped GaN ([Fe] up to $2x10^{18}$ cm^{-3}) resulting in high resistivity even at elevated temperatures.

Iron doping from ferrocen was introduced into the reactor and resulted in the required doping over the whole crystal thickness without additional strain in the layer and without negative impact on the reactor by, for example, enhanced parasitic growth. Moderate iron incorporation of up to $2x10^{18}$ cm^{-3} is sufficient to achieve excellent semi-insulating properties due to the high purity of the growth atmosphere, which results in carrier concentrations below 10^{16} cm^{-3} for the non-intentionally doped GaN layers. It is worth to note that a high resistivity of $2x10^{11}$ ohmcm is not only achieved at room temperature but stays above 10^{6} ohmcm up to elevated temperatures above 300°C (Fig. 3), which could occur at device junctions under high power operation.

This research activity was supported by the Federal Ministry of Education and Research (BMBF), project *TeleGaN* No. 16 BM 1202.

Galliumnitrid (GaN) bildet die Basis für viele Anwendungen in der Beleuchtungstechnik, Datenspeicherung, Leistungs- und Kommunikationselektronik. Bei der Herstellung von GaN-Substraten ist die HVPE die erfolgreichste Technologie, weil sie hohe Wachstumsraten [3] und gute Dotierungsmöglichkeiten [2] bietet. Semiisolierende Substrate aus GaN haben gute Aussichten, das bisher eingesetzte Siliziumcarbid abzulösen, da höhere Lebensdauern der Bauelemente erwartet werden. Das FBH erforscht das Wachstum mm-dicker GaN-Kristalle mit Durchmessern bis zu 4 Zoll, wobei die semiisolierenden Eigenschaften durch Dotierung mit Eisen aus der metallorganischen Quelle Ferrocen erzielt werden. Die Vergrößerung des Durchmessers von 2 auf 4 Zoll erforderte Designänderungen im Reaktorinneren, um eine gleichmäßige Verteilung der Gase über die Reaktionsfläche zu erreichen. Dabei gilt es durch die Wahl der richtigen Wachstumsparameter [1], Risse durch Minimierung von Verspannungseinbau in den Kristall zu vermeiden. Diese Entwicklung ist anhand simulierter und experimenteller Wachstumsraten, deren Verteilung und den erreichten, sehr guten isolierenden Eigenschaften selbst bei erhöhten Temperaturen in Fig. 1, 2 und 3 dargestellt.

Publications

[1] E. Gridneva, E. Richter, M. Feneberg, M. Weyers, R. Goldhahn, G. Tränkle, "Effect of carrier gas in hydride vapor phase epitaxy on optical and structural properties of GaN", phys. stat. sol. (b), 252, 1180 (2015).

[2] E. Richter, T. Stoica, U. Zeimer, C. Netzel, M. Weyers, G. Tränkle, "Si doping of GaN in hydride vapor-phase epitaxy", J. Electron. Mater. 42, 820 (2013).

[3] E. Richter, M. Gründer, B. Schineller, F. Brunner, U. Zeimer, C. Netzel, M. Weyers, G. Tränkle, "GaN boules grown by high rate HVPE", phys. stat. sol. (c), 8, 1450 (2011).

Precision laser scribing for formation of high-quality GaN laser facets

Group-III nitride laser diodes (LDs) can cover large parts of the visible to the ultraviolet spectral range. They are therefore highly attractive for a wide range of applications like displays, sensing, spectroscopy, and materials processing. To ensure high output powers, the deposition of high-quality coatings with defined reflectivity, and device reliability smooth mirror facets are crucial in edge-emitting LDs. Several methods have been used to fabricate high-quality mirror facets such as dry etching, polishing, and cleaving. Cleaving is the preferred method to obtain smooth and vertical facets for most semiconductor systems as it allows the crystal to break along its natural cleavage plane. However, the accuracy and the yield of edge-scribing and breaking using a diamond tip are limited by the crystal quality of both the epitaxial layers and the GaN substrate. Therefore, an alternative scribing process is required which does not damage the waveguides and its facet. We have developed a laser scribing process that employs the skip-and-scribe method using a nanosecond-pulsed frequency-tripled Nd:YAG laser.

The InGaN multi-quantum well laser diode heterostructures emitting around 395 nm were grown by metal organic vapor phase epitaxy on 2" c-plane n-type bulk GaN substrates. 200 µm thick bars with broad area (BA) LDs consisting of 1 µm thick p-contact metal stripes on the epitaxial structure and a plain metal layer on the bottom n-type substrate were fabricated. To achieve smooth mirror facets the photolithographic patterning was precisely aligned to the crystal's natural cleaving plane. The laser bar cleaving process always consisted of two steps: First, grooves were scribed on the epitaxial surface of the wafer along the m-plane of GaN, applying either a diamond tip or the laser. Second, the wafers were mounted to a supporting tape and cleaved along the scribed grooves using an impulse bar that hit the wafer from the bottom (substrate side). Laser scribing was performed in ambient air utilizing a frequency-tripled Nd:YAG laser delivering pulses at a wavelength of 355 nm. The laser machining parameters were optimized to minimize detrimental effects on cleaving properties (irregular breaking) and to achieve smooth mirror facets with low terrace density. Processing parameters were adjusted to minimize the formation of micro cracks due to laser-induced local heating.

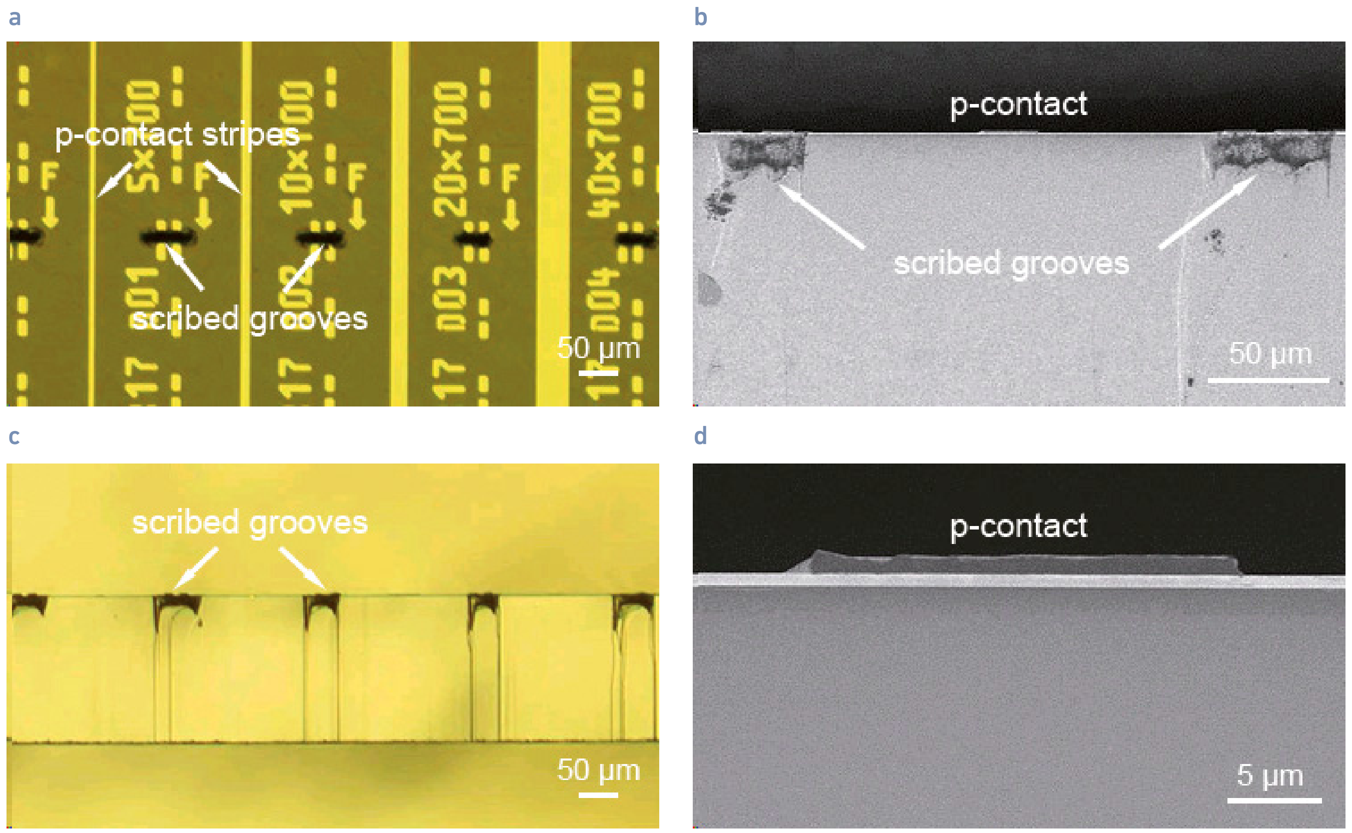


Fig. 1. Plan view optical micrographs of (a) a surface after skip-and-scribe laser machining and (b) a corresponding facet after cleaving. Cross sectional SEM micrographs (c, d) of a cleaved facet after laser scribing using 10 µJ laser pulse energy and 500 mm/min laser scan speed.

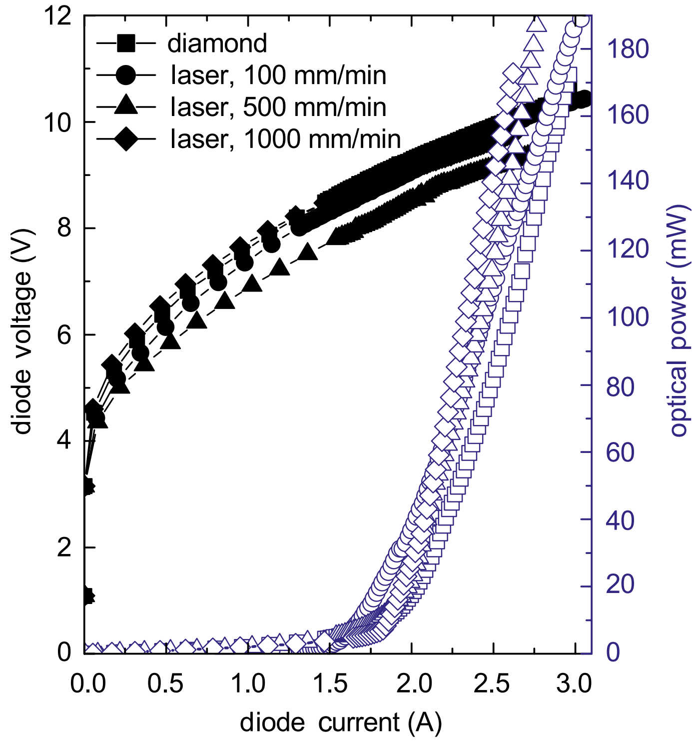


Fig. 2. Typical pulsed light output power and voltage vs. current characteristics of BA laser diodes (40 µm × 1300 µm), fabricated using diamond or laser scribing with 10 µJ laser pulse energy and laser scan speeds of 100 mm/min, 500 mm/min, and 1000 mm/min, respectively.

Re-deposited material alongside the scribes was removed from the surface by a wet-chemical treatment.

The mirror facets of laser diodes formed by the laser skip-and-scribe technique and subsequent cleaving were evaluated with respect to depth and length of the grooves. As shown in Fig. 1a, laser-scribed grooves were segmented and placed in between the p-type contact stripes with 70 µm distance to the metal edges to minimize any damage of the epitaxial structure in the lasing zone due to thermal effects or surface contamination by debris. The cleavage plane usually followed the designated track marked by the laser-scribed grooves. The cleaving was considered as correct when the cleavage is within a range of ± 25 µm from the center of the intended cleavage street over a length of 7.5 mm. Using this criterion, the yield of the cleaving process with the laser skip-and-scribe method was typically around 80 %, which is nearly a factor of 3 better than the diamond tip edge-scribe method. Furthermore, the cleavage planes of laser-scribed samples generally showed fewer terraces compared to those of diamond-scribed samples. Most of the terraces are located underneath the laser-scribed grooves, i.e., far off the p-contact stripe where they do not impair the performance of the LD. Even in the immediate vicinity of the laser treated zone, no detrimental effects on the crystal quality of the multi quantum wells could be detected by cathodoluminescence. The performance of laser bars fabricated with either the diamond tip edge-scribing method or the laser skip-and-scribe method is very similar. Various BA LDs with uncoated facets were characterized at room temperature under pulsed operation. Typical light output power and voltage versus current characteristics are exemplarily shown in Fig. 2 for lasers with 40 µm wide p-contact stripes and a cavity length of 1300 µm. Within the margins of the experimental errors there is no significant difference regarding threshold current density, threshold voltage, and slope efficiency for the different scribing methods. These data prove that there is no obvious impact of the scribing method on the electrical and the optical performance of the devices. By using the laser skip-and-scribe technique the propagation of the cleavage plane can be controlled, irregular breaking can be minimized, and the die yield can be significantly improved. Nanosecond-pulsed UV laser scribing followed by cleaving has been demonstrated to be a powerful technique for the formation of mirror facets of GaN-based LDs.

This work was partially funded by the Federal Ministry of Education and Research (BMBF) under contract no. 13N13023 and through the ProFIT program of Investitionsbank Berlin under contract no. 10157699.

GaN-basierte Laserdioden erfordern atomar glatte und parallele Spaltfacetten als Resonatorspiegel. Bei der Wafervereinzelung führt die klassische Technik des Diamantritzens und Spaltens jedoch oft zu fehlerhaften Spaltflächen. Der Grund dafür sind Kristalldefekte der gegenwärtig verfügbaren GaN-Substrate. Am FBH wurden daher aktive Laserstrukturen auf c-Flächen-GaN mittels eines UV-Lasers segmentiert geritzt sowie gebrochen und mit der konventionellen Diamantritzung an der Waferkante verglichen. Die Ausbeute an korrekt gebrochenen Laserriegeln ließ sich damit mehr als verdoppeln. Lichtausgangsleistung und Spannung wurden in Abhängigkeit vom Strom im Pulsbetrieb verglichen. Die Schwellenstromdichte, die Schwellenspannung und die differenzielle Effizienz für die unterschiedlichen Ritzmethoden sind dabei sehr ähnlich. Das segmentierte Laserritzen ist folglich gut geeignet, um ausreichend glatte Spiegelfacetten innerhalb definierter Spaltstraßen von Laserdioden auf c-Flächen-GaN-Substraten zu realisieren.

Publications

O. Krüger, J.-H. Kang, M. Spevak, U. Zeimer, S. Einfeldt, "Precision UV laser scribing for cleaving mirror facets of GaN-based laser diodes", Appl. Phys. A, 122(4), 396 (2016).

J.-H. Kang, O. Krüger, U. Spengler, U. Zeimer, S. Einfeldt, M. Kneissl, "On the formation of cleaved mirror facets of GaN-based laser diodes – A comparative study of diamond-tip edge-scribing and laser scribing", J. Vac. Sci. Technol. B 34(4), 041222-1 (2016).

III-V Technology III/V-Technologie

For further information:

http://www.fbh-berlin.com/research/iii-v-technology

Ferdinand-Braun-Institut
Leibniz-Institut für Höchstfrequenztechnik
Gustav-Kirchhoff-Str. 4
12489 Berlin, Germany
Phone +49.30.6392-2600
Fax +49.30.6392-2602
Email fbh@fbh-berlin.de
Web www.fbh-berlin.de

Editors *Redaktion*
Gisela Gurr, Petra Immerz

Layout & Typesetting *Layout & Satz*
Pitch Black Graphic Design, Berlin/Den Haag

Printing *Druck*
Prototyp Print, Berlin

Images & Graphics *Fotos & Grafiken*
K. Bilo: pp. 2, 38, 39 (top)
P. Immerz: pp. 9, 12, 13, 26, 34, 40, 46, 48 (3), 69 (top), 96 (1), 107
B. Schurian: pp. 10, 11, 14, 22, 23, 24, 27, 35, 47 (1), 48 (4), 56 (1), 63 (2), 66 (1), 72 (2), 78 (top)
G. Gurr: pp. 28, 60
TRUMPF: p. 21
A. Müller: p. 30
M. Keller: pp. 31, 32
A. Hultsch: p. 37
TNO: p. 39 (bottom)
M. Maiwald: p. 48 (5)
WeTeK: p. 49
F. Scheier: p. 51
N. Wolff: p. 85
J. Schmidt: p. 88
TU Berlin: p. 100 (2)
further / weitere: FBH

Leibniz
Ferdinand
Braun
Institut

Ferdinand-Braun-Institut
Leibniz-Institut für Höchstfrequenztechnik
Gustav-Kirchhoff-Str. 4
12489 Berlin

www.fbh-berlin.de