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IISB

FRAUNHOFER INSTITUTE FOR INTEGRATED SYSTEMS AND DEVICE TECHNOLOGY IISB

Fraunhofer Institute for Integrated Systems and Device Technology IISB

Annual Report 2019

ANNUAL REPORT 2019

Imprint

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Central power distribution for the ± 380 Volt DC network at Fraunhofer IISB.
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Backside Photo:
Acting director of Fraunhofer IISB Prof. Martin März explains to Bavarian Minister of Economic Affairs and Deputy Prime Minister Hubert Aiwanger (left) how sector coupling is implemented at Fraunhofer IISB and which significance the topic has for the Energiewende.
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Note to the Chapter „Names and Data“

The „Names and Data“ chapter is exclusively available in the online version of the annual report:

https://www.iisb.fraunhofer.de/annual_reports

It includes the following contents:
- Guest Scientists
- Patents
- Publications
- PhD Theses
- Master Theses
- Bachelor Theses

ACHIEVEMENTS AND RESULTS

ANNUAL REPORT 2019

FRAUNHOFER INSTITUTE FOR

INTEGRATED SYSTEMS AND DEVICE TECHNOLOGY IISB

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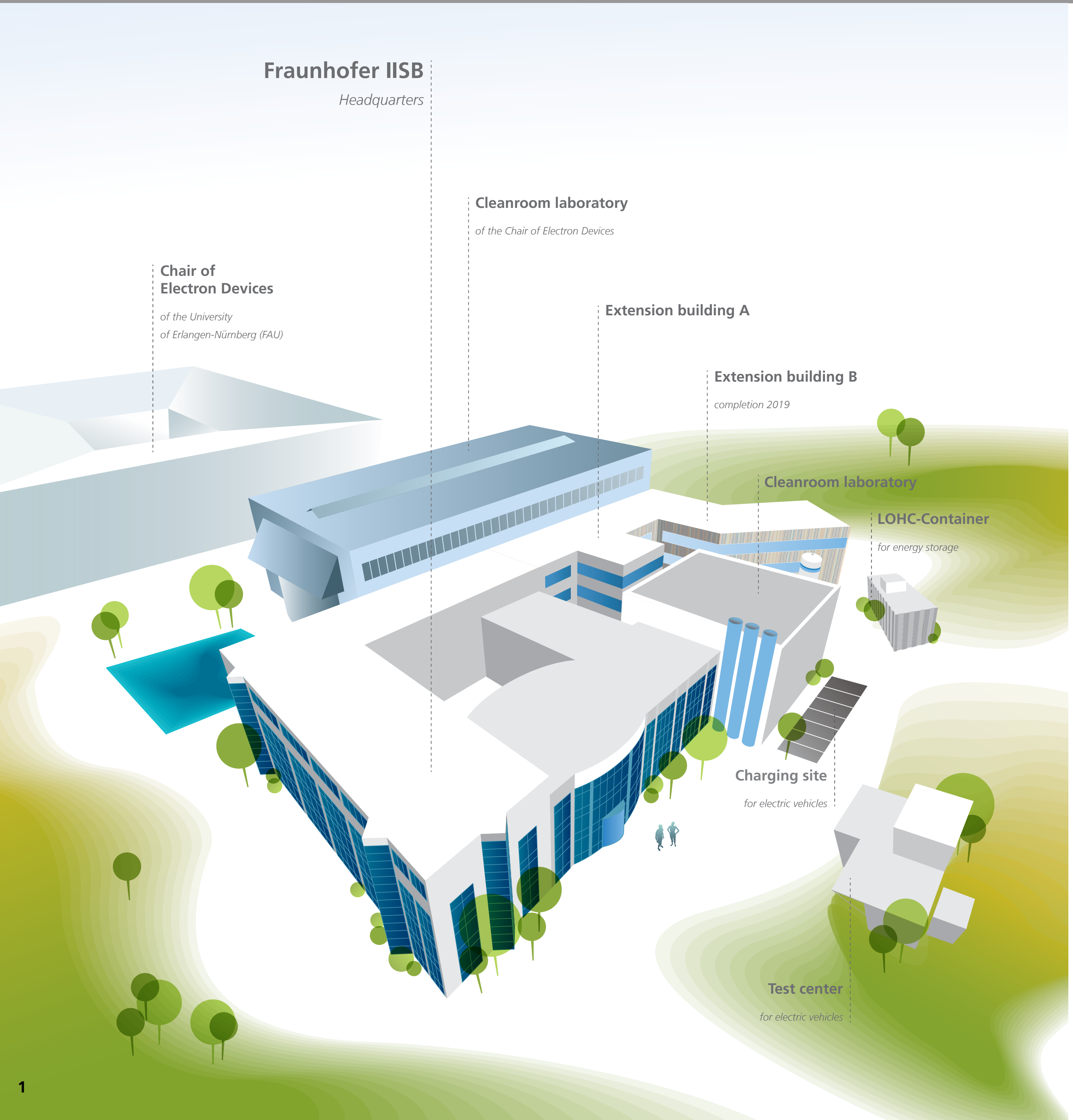
PREFACE



Sustainable energy supply and mobility are key elements in meeting the imminent environmental and economic challenges our society is facing. Superior solutions require fresh thinking and a comprehensive view of the overall system. At Fraunhofer IISB, this exactly constitutes the objective of our research on intelligent power electronic systems and technologies.

Our work on materials engineering, semiconductor technology, advanced packaging, and extensive system development, including a special focus on silicon carbide and other wide-bandgap semiconductors, explicitly addresses the demands of digitalization, energy efficiency, and climate protection.

In energy research, it is important to consider the complete, and partly complex, framework of generators, consumers, storages, and power grids. That was apparent also in our symposium on energy systems, held on the occasion of the ceremonial inauguration of our eagerly awaited latest extension building in Erlangen in July. The new office and laboratory complex offers an infrastructure which allows the highly flexible and efficient linkage of different forms of energy, using various modern storage technologies, an intelligent load management, data analytics and AI, renewable sources of energy, a powerful DC microgrid, a cogeneration unit, and our growing fleet of electric vehicles. Another highlight is a large medium-voltage application hall. This makes IISB a living lab on industrial scale.

In the current endeavors for global climate, electric driving is a key issue. The long-standing expertise of IISB in this field was underlined by our »Week of Electromobility« in September, including the IISB Annual Conference dealing with power electronics for electric vehicles, the 10-year anniversary edition of our BMBF-Fraunhofer student program DRIVE-E, as well as the public finish of the e-rally WAVE Germany 2019 on the central square of Erlangen.

I would like to thank all my colleagues for their magnificent work and the trusting collaboration in the past year. I also thank our partners in industry and all our funding authorities, especially the Bavarian Ministry of Economic Affairs, Regional Development and Energy as well as the German Federal Ministry of Education and Research (BMBF), for their support.

Now, I warmly encourage you to catch up on the latest work of Fraunhofer IISB presented in this report. Let yourselves be inspired!

Sincerely yours,
Prof. Dr. Martin März (Erlangen, February 2020)

1 *Schematic overview of the Fraunhofer IISB headquarters in Erlangen. © Fraunhofer IISB*

2 *Prof. Dr.-Ing. Martin März, director of Fraunhofer IISB. © K. Fuchs / Fraunhofer IISB*

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PROFILE AND HISTORY

PROFILE

The Fraunhofer Institute for Integrated Systems and Device Technology IISB conducts applied research and development in the field of electronic systems for application in, e.g., electric vehicles or energy technology. In this connection, the IISB extensively covers the complete value chain from basic materials to entire power electronic systems. With its two business areas, semiconductors and power electronics, the institute provides innovation and solutions in materials development, semiconductor technology and manufacturing, devices and modules, as well as in system development for vehicle power electronics, energy electronics, and energy infrastructures. This is supplemented by broad activities in reliability, simulation, characterization, and metrology.

The institute is located in Erlangen, Germany, and has branches in Nuremberg and Freiberg. As one of the 74 institutes of the Fraunhofer-Gesellschaft, the IISB does contract research for industry and public authorities. Moreover, it closely cooperates with the University of Erlangen-Nürnberg. The IISB has more than 250 employees plus numerous students working as research assistants. The institute is equipped with high-class laboratories, such as a test center for electric cars and an application center for DC grid technology. Together with the University, it operates 1500 m² of cleanroom area for semiconductor technology on silicon and silicon carbide.

The IISB is a close partner of national and international industry. Its main objective is to provide excellent research to its customers and to set technological benchmarks as one of the leading research institutions in electronic systems. Cooperation includes research and development projects, prototyping, consultancy, licensing, and studies.

HISTORY

The Fraunhofer Institute for Integrated Systems and Device Technology IISB in Erlangen is an important center of applied R&D for intelligent electronic systems, power electronics, semiconductor technology, and materials development in the Nuremberg metropolitan region, Germany, and Europe. It was founded in 1985 as the Electron Devices department AIS-B of the Fraunhofer Working Group for Integrated Circuits. In 1993, it became a Fraunhofer institute (IIS-B), but was still formally linked to its sibling institute IIS-A, today's Fraunhofer Institute for Integrated Circuits IIS. In 2003, IIS and IISB became completely independent from each other as two individual Fraunhofer institutes. From 1985 until 2008, Prof. Heiner Ryssel was the head of the IISB. From 2008 to 2018, Prof. Lothar Frey was director and currently Prof. Martin März leads the institute. From the beginning, the IISB has been closely cooperating with the University of Erlangen-Nürnberg (FAU). In 2015, IISB together with IIS and FAU founded the "Leistungszentrum Elektroniksysteme" (LZE).

ADVISORY BOARD 2019

IISB is consulted by an Advisory Board, whose members come from industry and research:

Dr. Stefan Kampmann (Chairman of the Advisory Board)
OSRAM Licht AG

Dr. Helmut Gassel
Infineon Technologies AG

Dr. Christina Hack
Brose Fahrzeugteile GmbH & Co. KG

Thomas Harder
European Center for Power Electronics (ECPE)

Prof. Dr. Joachim Hornegger
Friedrich-Alexander-Universität Erlangen-Nürnberg

Prof. Dr. Reinhard Lerch
Friedrich-Alexander-Universität Erlangen-Nürnberg

MinR Dr. Stefan Mengel
Federal Ministry of Education and Research (BMBF)

Petra Mönius
Conti Temic microelectronic GmbH

Dr. Andreas Mühe
PVA Crystal Growing Systems GmbH

Dr. Martin Schrems
AT&S AG

Dr. Thomas Stockmeier
ams AG

MR Dr. Stefan Wimbauer
Bavarian Ministry of Economic Affairs, Regional Development and Energy

ORGANIZATIONAL CHART 2019

DIRECTOR

M. März (acting)

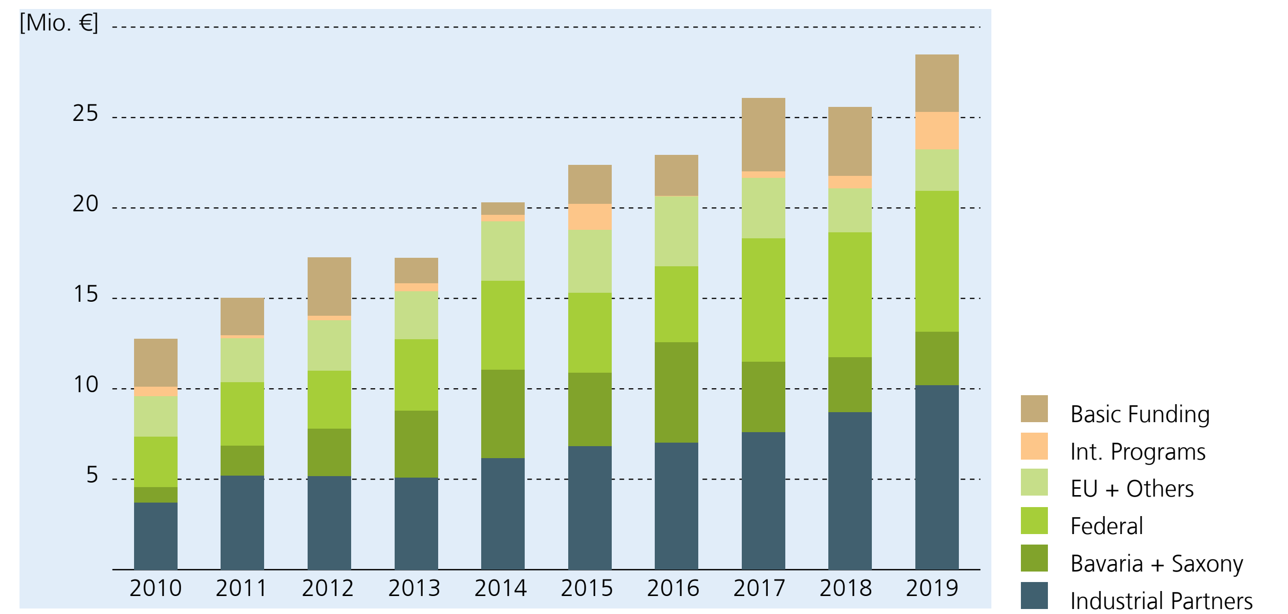
H. Hermes — ADMINISTRATION	J. Schöneboom — INFRASTRUCTURE
B. Fischer — STRATEGY & PR	G. Ardelean — IT

MODELING & ARTIFICIAL INTELLIGENCE J. Lorenz	MATERIALS J. Friedrich	TECHNOLOGY & MANUFAC-TURING A. Bauer	DEVICES & RELIABILITY A. Schletz	VEHICLE ELECTRONICS B. Eckardt	INTELLIGENT ENERGY SYSTEMS V. Lorentz
DOPING & DEVICES P. Pichler	SILICON C. Reimann	DEVICE PROCESSING V. Häublein	DEVICES T. Erlbacher	DRIVES & MECHATRONICS M. Hofmann	INDUSTRIAL POWER ELECTRONICS M. Billmann
STRUCTURE SIMULATION E. Bär	SILICON CARBIDE P. Berwian	THIN-FILM SYSTEMS M. Jank	PACKAGING C.Bayer	AC/DC CONVERTERS S. Zeltner	BATTERY SYSTEMS V. Lorentz
LITHOGRAPHY & OPTICS A. Erdmann	NITRIDES E. Meißner	NANO TECHNIQUES M. Rommel	TEST & RELIABILITY A. Schletz	DC/DC CONVERTERS S. Matlok	DC GRIDS B. Wunder
AI-AUGMENTED SIMULATION A. Roßkopf	ENERGY MATERIALS U. Wunderwald J. Heitmann	MANUFACTU-RING CONTROL M. Pfeffer		RF POWER & EMC C. Joffe	ENERGY TECHNOLOGIES R. Öchsner
	MATERIAL QUALIFICATION F. Beyer			GRID INTERFACES S. Endres	DATA ANALYTICS M. Schellenberger
	EQUIPMENT SIMULATION J. Friedrich			AEROSPACE ELECTRONICS F. Hilpert	
				MEDIUM VOLTAGE ELECTRONICS T. Heckel	

NUMBERS

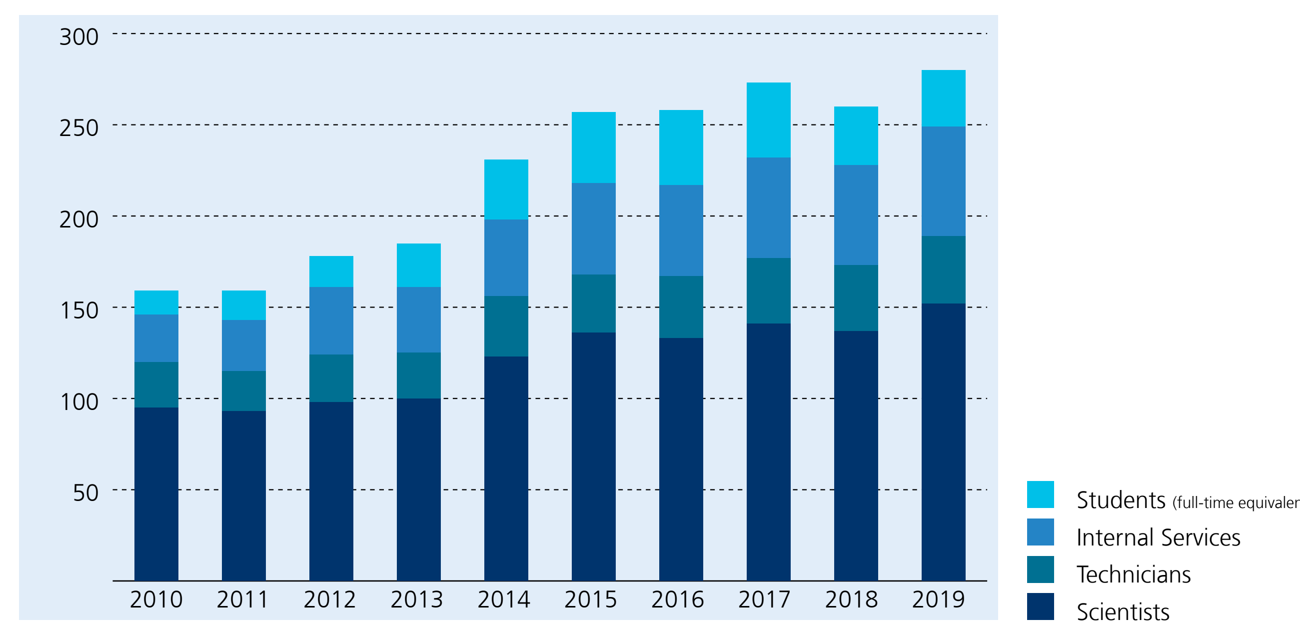
OPERATING BUDGET

28.6 Mio. € in 2019



STAFF DEVELOPMENT

280 Employees in 2019



RESEARCH AREAS

The R&D activities of the IISB cover the complete value chain for complex and intelligent electronic systems, from basic materials to devices and modules up to complete systems for application in mobility and energy technologies, with power electronics as a continuous backbone of the institute.

MATERIALS

Together with its industrial partners, the IISB develops equipment and processes for the production of crystalline bulk and layer materials for electronics. This comprises silicon, wide-band-gap semiconductors (e.g., silicon carbide, gallium nitride), materials for optical applications, detectors, and energy technology.

TECHNOLOGY & MANUFACTURING

The IISB operates extensive semiconductor technology lines, cleanroom infrastructure, and metrology on silicon and silicon carbide for the development of custom-tailored processes and prototype devices in power electronics and microelectronics. Furthermore, IISB works on nanotechniques, particle and thin-film systems. Manufacturing aspects such as process and quality control, equipment optimization, automation, and efficiency are also considered.

MODELING & ARTIFICIAL INTELLIGENCE

The research activities of the IISB and its customers are supported by extensive competencies in simulation, modeling, and software development in the fields of, e.g., process and device simulation in semiconductor technology, AI augmented simulation, crystal growth simulation, or thermal simulation for designing power electronic systems.

DEVICES

The institute develops customer-specific active and passive electron devices on silicon and silicon carbide for application in power electronics, microelectronics, and sensors. This includes novel device concepts and the development of cost-efficient processes tailored towards implementation and realization of customized products.

PACKAGING & RELIABILITY

New methods and materials for packaging, cooling, lifetime and failure analysis, and reliability play an important role. At IISB, packaging and reliability research are closely combined with each other. By analyzing the exact failure mechanisms after lifetime and reliability tests, the joining technologies, materials, concepts and mechanical designs are further improved. On the other hand, new packaging designs have a direct impact on the test methodologies and accelerating factors.

VEHICLE ELECTRONICS

Efficient, compact, and robust power electronic systems for all kind of vehicles are in the focus of the IISB. This comprises electric drives, battery systems, and the charging infrastructure of electric cars. Benchmark values for energy efficiency and power density are regularly set for the work of the IISB. Further fields of application are shipping and aviation.

INTELLIGENT ENERGY SYSTEMS

Power electronic systems are indispensable for realizing a modern energy supply and the transition to predominantly regenerative energy sources. The developments of the IISB contribute to this on all levels of the power grid through, e.g., electronic components for HV DC transport, local DC micro grids or the integration of electrical storages and regenerative sources in the power grid.

ENERGY INFRASTRUCTURE TECHNOLOGIES

The goal of this field of activity is the coupling of electric and non-electric energy and the development of the necessary interfaces for implementing a sustainable energy infrastructure, especially for industry-size environments.

LOCATIONS

HEADQUARTERS OF FRAUNHOFER IISB ERLANGEN

Schottkystrasse 10, 91058 Erlangen

The headquarters of Fraunhofer IISB in Erlangen are located close to the University of Erlangen-Nürnberg. About 10,000 m^2 of laboratories and office area allow research and development on a broad range of power electronics, semiconductor technology, and materials development. A test center for electric cars, a medium-voltage application hall, an application center for DC grid technology, and extensive cleanroom area for semiconductor technology on silicon and silicon carbide, which is partly operated together with the Chair of Electron Devices of the University, are part of the available infrastructure.

BRANCH LABS OF FRAUNHOFER IISB

Fraunhofer IISB Nuremberg-EnCN
Fürther Strasse 250, "Auf AEG", 90429 Nuremberg

As a member of the "Energie Campus Nürnberg" (EnCN), the IISB operates a branch lab on megawatt power electronics for energy supply in the joint EnCN building in Nuremberg.

Technology Center for Semiconductor Materials THM Freiberg
Am St.-Niclas-Schacht 13, 09599 Freiberg

The THM is a joint department of Fraunhofer IISB and Fraunhofer ISE. It supports industry in technologies for the production of innovative semiconductor materials to be used in microelectronics, optoelectronics, and photovoltaics. The IISB part of the THM comprises 650 m^2.

NETWORK AND PARTNERS

Within its research activities, Fraunhofer IISB pursues cooperation with numerous national and international partners in joint projects and associations, among others:

- Since its foundation, the IISB has been closely cooperating with the University of Erlangen-Nürnberg (FAU). The institute is directed by the head of the Chair of Electron Devices of the University. The joint operation of infrastructure as well as the exchange in education and training create extensive synergies.
- The IISB is a core member of the "Leistungszentrum Elektroniksysteme" (LZE, www.leistungszentrum-elektroniksysteme.de, www.lze.bayern).
- The IISB is a member of the "Research Fab Microelectronics Germany" (FMD, https://www.forschungsfabrik-mikroelektronik.de).
- The IISB is the coordinator of the Bavarian energy research project SEEDs (www.energy-seeds.org).
- The IISB is a member of the "Energie Campus Nürnberg" (EnCN, www.encn.de).
- The IISB is a partner of the excellence projects at the University of Erlangen-Nürnberg (www.eam.uni-erlangen.de, www.aot.uni-erlangen.de/saot/).
- The IISB closely cooperates with industry and research associations, such as the European Center for Power Electronics, the Bavarian Clusters for Power Electronics and Mechatronics & Automation, or the German Crystal Association DGKK e.V.
- The IISB is the coordinator and partner, respectively, of numerous European research projects.
- Together with the Federal Ministry for Education and Research (BMBF), the IISB initiated and operates the joint student program of BMBF and Fraunhofer for electric mobility, DRIVE-E (www.drive-e.org).
- The IISB is a close partner of the "Förderkreis für die Mikroelektronik e.V."
- The IISB is in close cooperation with the Technical University TU Bergakademie Freiberg in the area of semiconductor materials

The IISB is member of the following Fraunhofer groups and alliances:

- Fraunhofer Group for Microelectronics (www.mikroelektronik.fraunhofer.de)
- Fraunhofer Energy Alliance (www.energie.fraunhofer.de)
- Fraunhofer Battery Alliance (www.batterien.fraunhofer.de)
- Fraunhofer Nanotechnology Alliance (www.nano.fraunhofer.de)

NETWORK AND PARTNERS

CHAIR OF POWER ELECTRONICS (LEE), UNIVERSITY OF ERLANGEN-NÜRNBERG (FAU)

Since September 1, 2016, Prof. Dr. Martin März, acting director at Fraunhofer IISB, is heading the Chair of Power Electronics (LEE). The chair conducts research on current topics in the field of power electronics for electric power supply. Besides stationary decentralized electrical power systems, the addressed application fields also include the power-grids in vehicles, ships, railways, and airplanes. LEE is part of the Energy Campus Nuremberg (EnCN) in the Fürther Strasse in Nuremberg, and the first chair grown out of the EnCN.

CHAIR OF ELECTRON DEVICES (LEB), UNIVERSITY OF ERLANGEN-NÜRNBERG (FAU)

The Fraunhofer IISB and the Chair of Electron Devices (German abbreviation: LEB) of the University of Erlangen-Nürnberg are both currently headed by Prof. Martin März as acting director.

Within the framework of a cooperation agreement, the two institutions not only jointly operate the University's cleanroom hall and other laboratories, but also work closely together with regard to teaching and research.

The cooperation of the Chair of Electron Devices and the Fraunhofer IISB makes it possible to cover the entire chain of topics from basic research to the transfer to industry. For many years, the vocational training as a "microtechnologist" has been offered jointly by IISB and the Chair of Electron Devices. Employees of IISB assist in courses and internships at the University.

1 *Chair of Electron Devices of the University of Erlangen-Nürnberg: main building and clean room laboratory.*
© LEB

The following staff members of Fraunhofer IISB regularly give lectures at the University of Erlangen-Nürnberg:

Dr. Andreas Erdmann
- Optical Lithography: Technology, Physical Effects, and Modeling

Dr. Tobias Erlbacher
- Semiconductor Power Devices
- Prozessintegration und Bauelementearchitekturen
- Technologie Integrierter Schaltungen

Dr. Jochen Friedrich
- Course on Crystal Growth

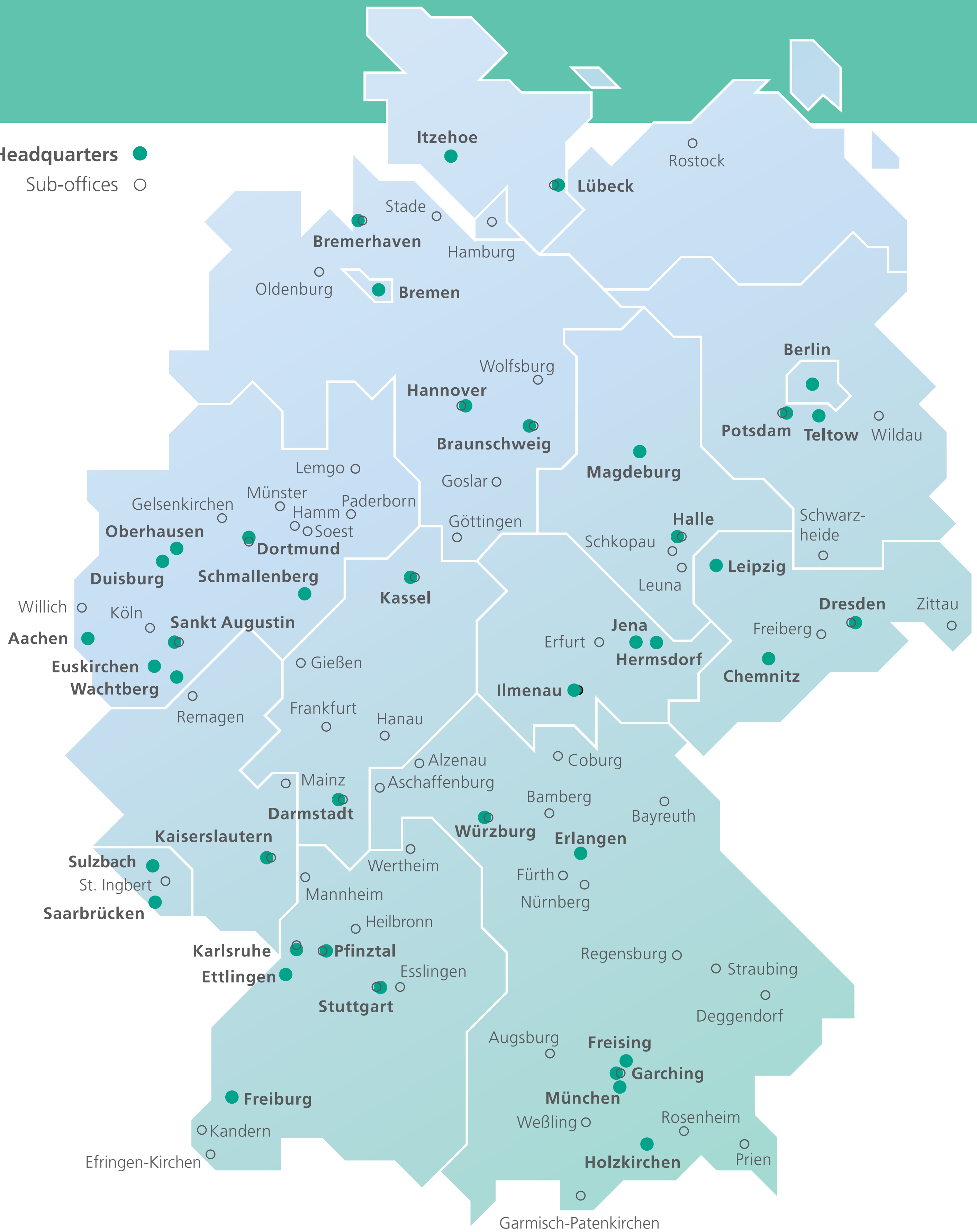
Dr. Michael Jank
- Introduction to Printable Electronics
- Nanoelectronics

Dr. Jürgen Lorenz
- Process and Device Simulation

Prof. Dr. Martin März
- Power Electronics for Decentralized Energy Supply - DC Grids
- Power Electronics in Vehicles and Electric Powertrains
- Thermal Management for Power Electronics
- Technische Isoliersysteme und deren Zustandsdiagnose
- Power Electronics

Priv.-Doz. Dr. Peter Pichler
- Reliability and Failure Analysis of Integrated Circuits

THE FRAUNHOFER-GESELLSCHAFT



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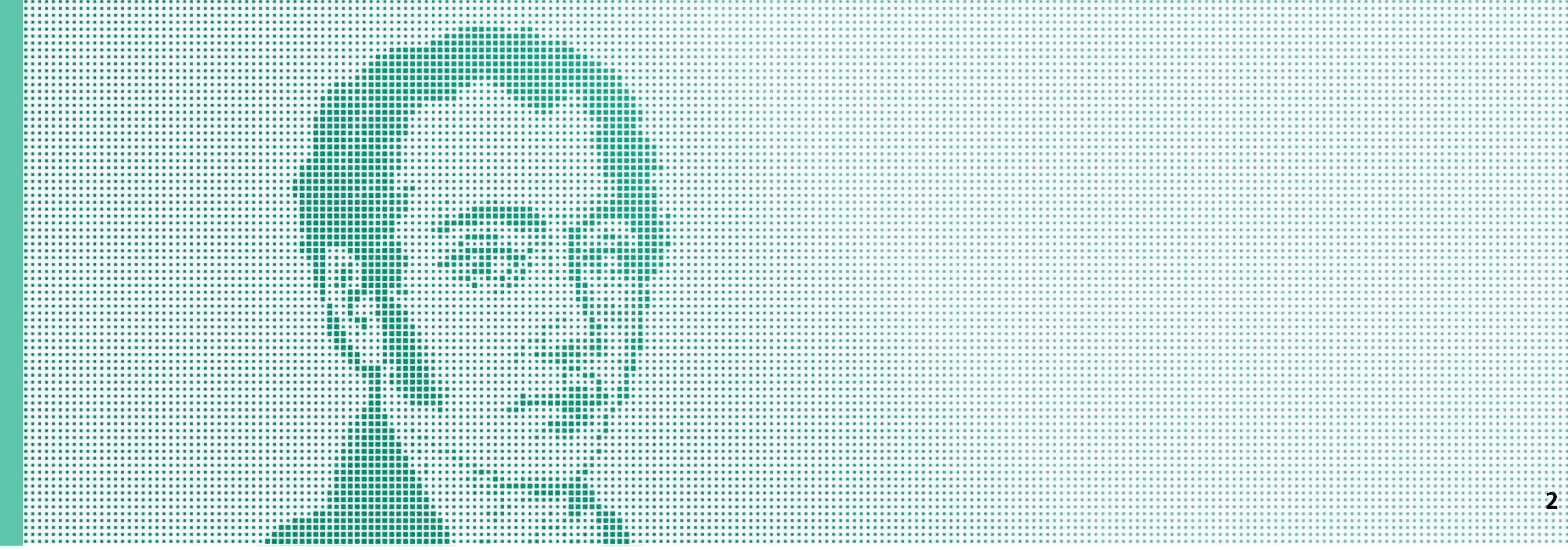


2

The Fraunhofer-Gesellschaft is the world's leading applied research organization. With its focus on developing key technologies that are vital for the future and enabling the commercial exploitation of this work by business and industry, Fraunhofer plays a central role in the innovation process. Based in Germany, Fraunhofer is an innovator and catalyst for groundbreaking developments and a model of scientific excellence. By generating inspirational ideas and spearheading sustainable scientific and technological solutions, Fraunhofer provides science and industry with a vital base and helps shape society now and in the future.

At the Fraunhofer-Gesellschaft, interdisciplinary research teams work together with partners from industry and government in order to transform novel ideas into innovative technologies, to coordinate and realize key research projects with a systematic relevance, and to strengthen the German and the European economy with a commitment to creating value that is based on human values. International collaboration with outstanding research partners and companies from around the world brings Fraunhofer into direct contact with the key regions that drive scientific progress and economic development.

Founded in 1949, the Fraunhofer-Gesellschaft currently operates 74 institutes and research institutions. The majority of our 28,000 staff are qualified scientists and engineers, who work with an annual research budget of 2.8 billion euros. Of this sum, 2.3 billion euros is generated through contract research. Around 70 percent of Fraunhofer's contract research revenue is derived from contracts with industry and publicly funded research projects. The remaining 30 percent comes from the German federal and state governments in the form of base funding. This enables the institutes to work on solutions to problems that are likely to become crucial for industry and society within the not-too-distant future.

Applied research also has a knock-on effect that is felt way beyond the direct benefits experienced by the customer: our institutes boost industry's performance and efficiency, promote the acceptance of new technologies within society, and help train the future generation of scientists and engineers the economy so urgently requires.

Our highly motivated staff, working at the cutting edge of research, are the key factor in our success as a scientific organization. Fraunhofer offers researchers the opportunity for independent, creative and, at the same time, targeted work. We therefore provide our employees with the chance to develop the professional and personal skills that will enable them to take up positions of responsibility at Fraunhofer, at universities, in industry and within society. Students who work on projects at Fraunhofer Institutes have excellent career prospects in industry by virtue of the practical training they enjoy and the early experience they acquire of dealing with contract partners.

1 *Locations of the Fraunhofer-Gesellschaft in Germany.*
The Fraunhofer-Gesellschaft is a recognized non-profit organization that takes its name from Joseph von Fraunhofer (1787–1826), the illustrious Munich researcher, inventor and entrepreneur.
© Fraunhofer

2 *Joseph von Fraunhofer.*
© Fraunhofer IISB

RESEARCH FAB MICROELECTRONICS GERMANY

Forschungsfabrik Mikroelektronik Deutschland

1

ONE-STOP-SHOP: MICROELECTRONICS INNOVATION FROM FUNDAMENTAL RESEARCH TO PILOT PRODUCTS

1 *Omega- and theta-scan for oriented gluing of crystals from new semiconductor materials with large band gaps.*
© Kurt Fuchs / Fraunhofer IISB

Since April 2017, Fraunhofer IISB is part of the Germany-wide Research Fab Microelectronics Germany (FMD). With 13 member institutes and over 2000 active researchers, this research network represents Europe's largest R&D collaboration for micro and nanoelectronics.

The investments in FMD are paying off

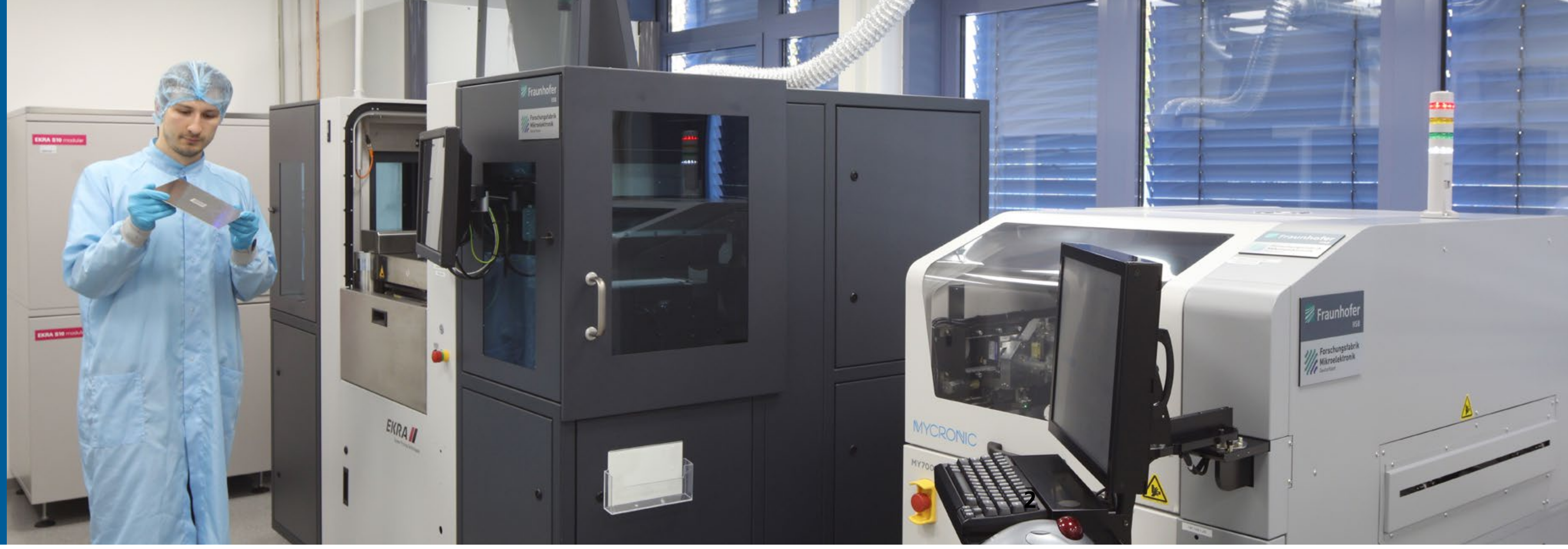
Within the last two and a half years, successful project ventures have been established and numerous contracts completed in cooperation with the FMD. In 2019, projects with an FMD-wide overall volume of €66.8 million were made possible as a result of investments into the FMD. Pure industry projects accounted for more than €17 million in 2019, underlining the importance of this unique cooperation in German microelectronics research.

In 2020, the final set-up phase for the Research Fab Microelectronics Germany is being initiated. The FMD is a promising model for major project initiatives. The innovative concept's great potential for cross-site cooperation has already been proven, e.g. in the frame of the Leitban project. The project aims at developing aluminum nitride as the new semiconductor material for highly efficient power semiconductors, to test it with suitable devices and to qualify it for future applications in systems. Until 2023, the project will be funded with €3.3 million by the Federal Ministry of Education and Research within the ForMikro program.

Within the project, Fraunhofer IISB (AlN crystal growth, wafer manufacturing) is collaborating with the Ferdinand-Braun-Institut (AlN device design and development), which is also part of the FMD, and the TU Bergakademie-Freiberg (process module development, analytics), the Friedrich-Alexander-Universität Erlangen-Nürnberg (material analysis), the Brandenburgische Technische Universität Cottbus-Senftenberg (AlN millimeter wave systems), and the Technische Universität Berlin (AlN power electronic systems).

Founders' dreams come real in the FMD-Space. The start-up support concept FMD-Space – first proposed at the very start of the FMD's set-up – has continued to make headway in 2019 in several successful pilot projects. Technology-driven start-ups are thus provided efficient and ready access to the technologies and facilities of the member institutes. The enterprising minds behind the start-ups team up with the institutes' research staff to produce working demonstrators of their product concepts.

RESEARCH FAB MICROELECTRONICS GERMANY



The FMD vision of successful research and development work happening collaboratively at locations across Germany is supported by Germany's Federal Ministry of Education and Research, with approx. €350 million in funding set aside until late 2020. This investment into the FMD fuels the future viability of applied microelectronics research in Germany. Practically, this primarily takes the form of updated and modernized research facilities at the 13 participating institutes from the Fraunhofer-Gesellschaft and Leibniz Association. By the end of 2019, 157 new pieces of equipment have already been delivered and are, in the main, already up and running – a great step forward in substantially expanding the institutes' technological capabilities.

FMD at Fraunhofer IISB

Within FMD, Fraunhofer IISB has a unique selling point with its integrated, certified production line for the processing of individual SiC-based prototype devices in an industry-compliant environment.

In the front-end area for wafer sizes of mainly 150 mm, all necessary process steps can be performed at Fraunhofer IISB, such as epitaxy, ICP dry etching, growth of silicon dioxide, aluminum implantation at elevated temperatures, activation anneal, and metallization. Usually, vertical devices are manufactured in SiC for power electronics. Therefore, the processing of the backside of the SiC wafers is of critical importance. The FMD investments now also enable the bonding and debonding of already finally processed wafers at the front side, the thin grinding of wafers at the backside and the reduction of contact resistance at the rear side by means of advanced metallization and laser silicidation.

New integration technologies and innovative assembly and system concepts for prototyping and the production of future power modules are available in the backend area. This makes it possible, for example, to realize particularly complex and compact structures, heavily stressed (special) applications with sometimes small quantities or durable high-temperature power electronic modules.

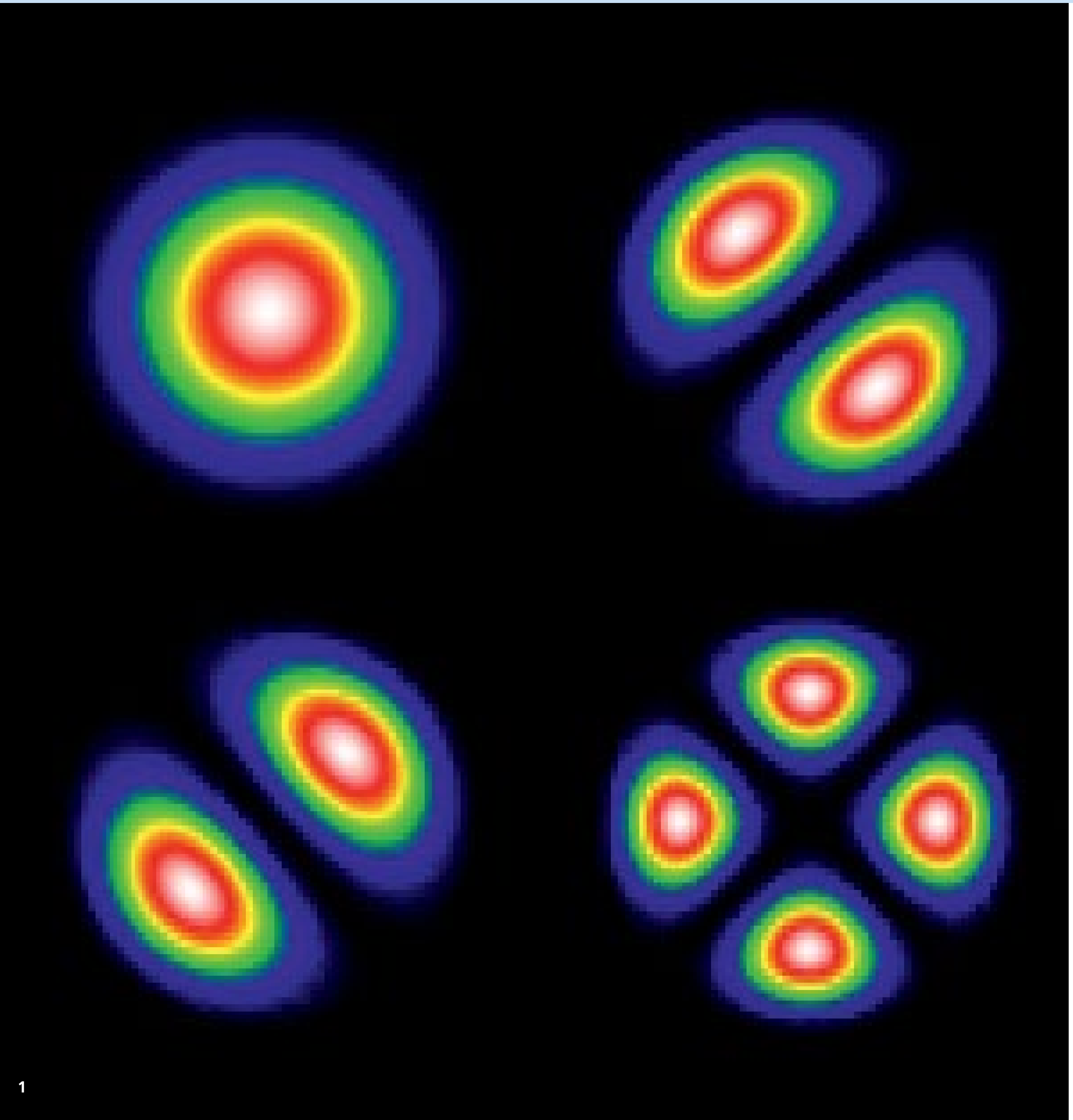
Extensive, complementary methods are available along the process chain for quality control. The most important of these are a fast, high-resolution X-ray topography system for the analysis of the structural properties of crystals, wafers and partially processed wafers, and a combined surface inspection photoluminescence device for the analysis of the near-surface material properties of SiC along the process chain. The SiC metrology is supplemented by special measuring stations, which are adapted to the specific, sometimes extreme conditions of power electronics, such as an extra-high voltage measuring station as well as special lifetime and reliability test laboratories.

For the research on new semiconductor materials with large band gaps, crystals of these materials are needed, which then have to be further processed into wafers in order to evaluate the potential in FMD for power electronics or for other applications such as in quantum technology. Since the new crystal materials, such as GaN, AlN or diamond, are usually crystals with small diameters (50 mm or smaller), Fraunhofer IISB operates a special substrate and wafer laboratory to produce wafers from such crystals. The quality of the wafers used to manufacture the devices is tested using various analytical methods, including the determination of their epitaxial suitability and the production of special test structures.

You will find more information about the Research Fab Microelectronics Germany at https://www.forschungsfabrik-mikroelektronik.de/

2 *Cleanroom packaging laboratory: Modern paste printing systems for flexible die attach.*
© Kurt Fuchs / Fraunhofer IISB

MODELING AND ARTIFICIAL INTELLIGENCE



Modeling and simulation has during the last decades established itself as indispensable for the development and optimization of technologies and applications in most industrial areas. Its methods range from first-principle calculations done on the atomic or molecular scale through multiphysics simulations to large-area simulations using heuristic models, which do not solve detailed physical equations but employ simplified analytical expressions and elaborated methods for extraction of the parameters required. At IISB, currently numerical methods are complemented by approaches from data science, known as Artificial Intelligence (AI).

In micro and nanoelectronics, the simulation of semiconductor fabrication processes, devices, circuits, and systems (the so-called Technology-Aided Design TCAD) has a great share in the reduction of development costs in the semiconductor industry. Among others, this was confirmed for micro- and nanoelectronics already in the 2013 issue in the International Technology Roadmap for Semiconductors (ITRS). The department "Modeling and Artificial Intelligence" contributes to this by developing physical models and programs for the simulation and optimization of semiconductor fabrication processes and equipment. Furthermore, it supports the characterization and optimization of lithography (incl. masks, materials, and imaging systems) and other processes, devices, circuits, and systems by providing and applying its own and third-party simulation and optimization tools. Whereas the research effort on the modeling and simulation of processes for aggressively scaled devices has since the foundation of the institute been the core of the activities of the department, in recent years the activities of the department have been strongly extended into the area of "More than Moore", which consists of fields such as analog/RF, low-power electronics, power electronics, and microsystems technology. These new fields of application in particular often require the combination of heterogeneous competencies, because thermal, mechanical, optical, and chemical effects also occur in addition to electronic effects. This gives rise to an additional demand for research.

Addressing scaling of nanoelectronic devices

The department also continues to make important contributions to support the further scaling of advanced nanoelectronic devices. These activities have been mainly carried out in five cooperative projects on the European level, funded by the European Commission and in some cases also by the member states:

The EU Horizon 2020 project "Stability Under Process Variability for Advanced Interconnects and Devices Beyond 7 nm Node" (SUPERAID7) coordinated by the department has dealt with the simulation of the impact of process variations on advanced transistors and circuits. SUPERAID7 has been completed very successfully at the beginning of 2019. More information on this project

1 *Square of quantum mechanical wave function for particle in a circular well (example from IISB in project IONS4SET): Ground state (upper left) and three exited states.*

2 *Dr. Jürgen Lorenz, head of the Modeling and Artificial Intelligence department. © Kurt Fuchs / Fraunhofer IISB*

MODELING AND ARTIFICIAL INTELLIGENCE

Physics and Artificial Intelligence: No Competitors but Together Ever More Useful

was given in a dedicated article in the preceding annual report for 2018, where it was also outlined how this project has contributed to the so-called "Design-Technology Co-Optimization" (DTCO), which is now a key tool to support developments in semiconductor industry.

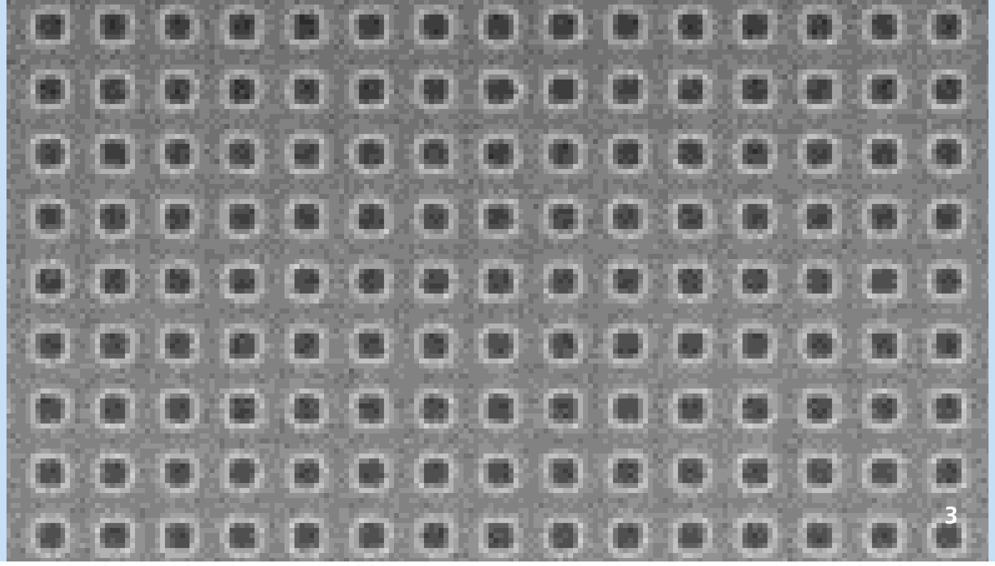
The Horizon 2020 project "Ion-irradiation-induced Si Nanodot Self-Assembly for Hybrid SET-CMOS Technology" (IONS4SET), coordinated by the Helmholtz Zentrum Dresden-Rossendorf, aims at merging of single electron transistors, granting low-power consumption, and CMOS technology, providing speed, performance and integrability. Here, the department uses simulation to assess technological options and device performance.

The traditionally optics-driven resolution improvements through extreme ultraviolet (EUV) lithography have been addressed in the ECSEL KET pilot lines "Technology Advances and Key Enablers for 5 nm" (TAKE5 - finished end of March 2019), "Technology Advances for Pilotline of Enhanced Semiconductors for 3 nm (TAPES3) and „Pilot Integration of 3 nm Semiconducter Technology" (PIn3S – started October 2019). The new PIn3S project aims to launch a pilot production line of 3-nanometer semiconductor technology. The focus is on optimizing process integration, and developing new lithography, mask repair and metrology tools. These key lithography projects have been or are carried out by large consortia of companies, research institutes, and universities, coordinated by ASML, the leading vendor of lithography steppers. For each of them, the German part is coordinated by Zeiss. The department contributes with the extension and especially with the application of its leading-edge lithography simulator Dr.LiTHO. In several activities of the department, lithography simulation is used not only for the development of advanced lithography technology but also for metrology and inspection.

Furthermore, the department also earns license fees for software developed within "More Moore" projects. Our solid expertise gained in the field of "More Moore", for instance regarding tailored numerical methods for model implementation, provides a sound basis for the development and application of simulation in other fields, such as "More than Moore".

Software engineering and Artificial Intelligence

Software engineering techniques are developed and applied in various areas of the institute, among others for smart battery management, which is an important research topic in power electronics. Genetic algorithms, neural networks, and hierarchical modeling approaches are utilized for component and system optimization. Multiphysics simulations that include electrical, mechanical, and/or thermal effects on a case-by-case basis are employed for applications especially in the power electronics area. Methods based on Artificial Intelligence have been increasingly used to enhance traditional approaches for modeling, simulation, and optimization, especially on system level. Key information hidden in large data sets including signals and pictures can be extracted in a largely automated and parallelized way to describe and optimize systems at all levels. The challenge and approach is not to replace physics-based modeling and simulation by data science based predictions, but to combine and utilize the strengths of these two complementary approaches. In order to highlight this approach and mission, at the beginning of 2019 the department Simulation was renamed to "Modeling and Artificial Intelligence", and a new group "AI-Augmented Simulation" was founded in order to implement and exploit this approach especially for the optimization of power electronic systems.



3 *SEM picture of an EUV mask.*

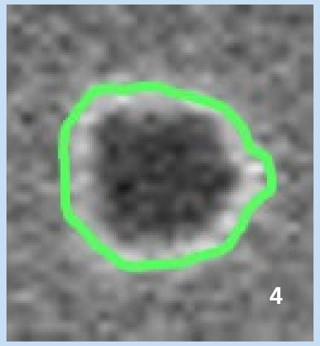
Conclusions and outlook

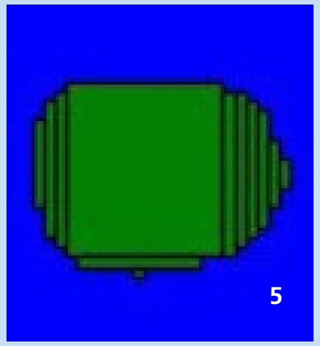
In the various areas of "More Moore", "More than Moore", and Power Electronics, the expertise gained or expanded in publically funded cooperative projects also provides the foundation for several research and development projects directly commissioned and financed by industry, e.g., for the optimization of lithography or the simulation of platinum diffusion for power devices.

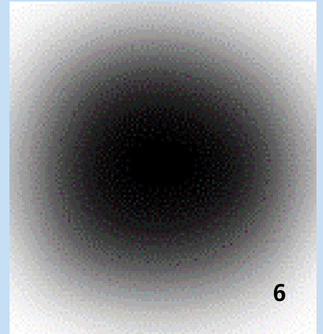
The department will continue its approach to performing focused work on physical models and algorithms in order to develop the necessary skills and tools on the one hand and to transfer these results to applications in industry on the other. Especially, the combination of physical understanding with the additional capabilities of data science implemented in AI approaches considerably extends the capabilities of the department to provide promising research results and valuable support to industry. Here, a close and trustful cooperation based on sharing work according to the individual competencies and requirements of the partners has been a key element of the success achieved for many years.

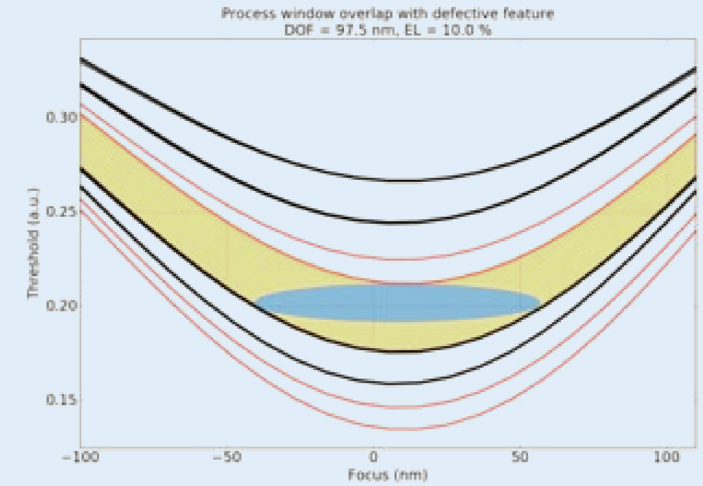
PHYSICS AND ARTIFICIAL INTELLIGENCE: NO COMPETITORS BUT TOGETHER EVER MORE USEFUL

"Artificial Intelligence" (AI) nowadays seems to be a buzzword, raising broad expectations that it can solve many – or most – problems in numerous areas. Is the institute just following the crowd, among others by having renamed its department "Simulation" into "Modeling and Artificial Intelligence"? No – we have been using selected approaches from the AI area for about 15 years to enable specific applications. Due to the huge growth of computing power – among others enabled by the industrial use of TCAD – the possibilities for AI have in the meantime grown tremendously. In turn, the IISB is using methods from AI increasingly for various applications, ranging from nano to power electronics.









4 *Single defective mask feature: Greytone image and extracted sharp contour line.*

5 *Manhattan structure generated on the computer to represent a defective mask structure.*

6 *Aerial image simulated with Dr.LiTHO.*

7 *Process window of EUV lithography step without (black) and with (red) defect.*

Microelectronics and computing push each other

The huge capabilities of microelectronics and its complexity are two sides of the same medal: For many years now, the simulation of processes, devices, and circuits is an indispensable part of the development of microelectronic devices, circuits, and systems. On the other hand, the enormous growth of the computing power allows both for simulations with more complex physical models and for the extraction of information from ever growing data sets. Among others, approaches from supervised, unsupervised, and enforced learning are applied for the analysis, prediction, and optimization of the performance, stability (and costs) of complex systems. Such approaches from data science are examples of "Artificial Intelligence". They frequently complement and at best are combined with physical simulations.

Early results from AI at IISB

Among others, already 15 years ago we used so-called "Genetic Algorithms" (GAs) for global optimization in lithographic applications. Here, a large number of process and mask parameters must be selected to optimize the structure generated in terms of nominal values (e.g., feature size) and its stability against process variations. A Genetic Algorithm mimics the natural evolution process, which consists of selection, recombination, and mutation (here of parameter vectors) on a computer. Its main advantages are that it does not get stuck in local optima but finds the best global value, that boundary conditions and restrictions can be easily satisfied via the so-called fitness functions used, and that it can be easily implemented on parallel computers. Other departments of the institute used AI already long ago among others for Predictive Maintenance, where, e.g., Bayesian Networks were used to predict equipment breakdown from data recorded during equipment operation.

High-quality data and physical simulation for AI

The key for the successful application of AI methods like the various kinds of Neural Networks is the quality of the data used for their training, which must very well represent the system to be studied in all its modes of operation or failure in question. Here, the broad competence of the institute in semiconductor equipment, technologies, systems, and applications assures the quality of the relevant data used. Furthermore, physical simulation can be and is used to provide complementary data for domains where measured data is not available. In consequence, at IISB AI methods like data analysis and neural networks are complemented with (multi)physical simulations, and include digital twins. Here, the department "Modeling and Artificial Intelligence" (MKI) and its group "AI-augmented simulation" conduct crosscut research starting from physical models and AI algorithms, whereas AI activities, e.g., in the departments "Intelligent Energy Systems" and in its group "Data Analytics" are driven by data acquisition, quality, and usage based on detailed knowledge of the domain.

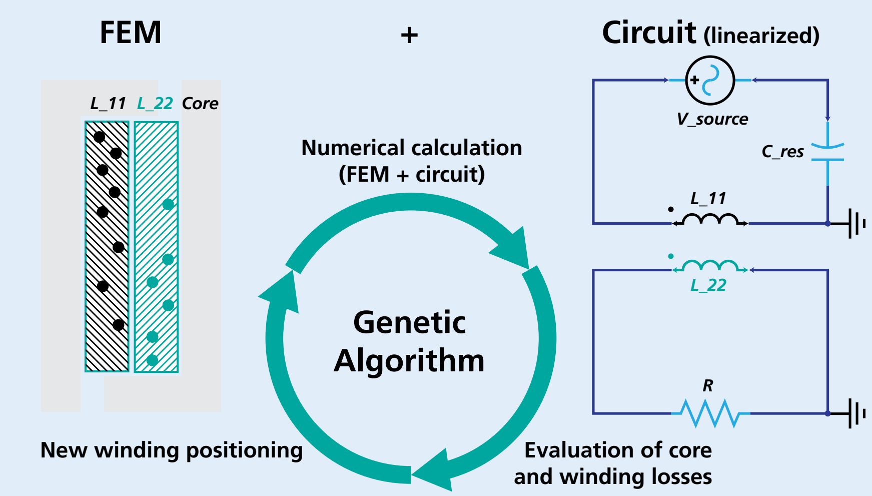
Examples from nano to power electronics

Current AI activities in the department MKI range from optimization in nanoelectronics to power electronic systems. One example for the combination of supervised learning with physical simulation in the department MKI is the characterization and assessment of defects in masks for Extreme Ultraviolet Lithography (EUV): EUV is the leading-edge lithography technique currently foreseen for the production of chips based on the most advanced nanoscale transistors. The aim of our work is to easily and efficiently decide if a mask is defective or not, based on the image generated by the mask (the so-called aerial image). In principle, Scanning Electron Microscope (SEM) pictures of the mask (Fig. 3) could be used to train neural networks. However, in real cases the SEM pictures do not contain sharp structures but smooth transitions between black and white. Methods from image processing are used to convert single features from these SEM pictures into the closed rectangular polygons (so-called "Manhattan structures") needed as input for lithography simulation (Fig. 4). However, the SEM data basis is not sufficiently broad and does not sufficiently cover the possible defect classes. Instead, the Manhattan structures are generated for the non-defective structures, and all relevant defect classes are added to these structures on the computer (Fig. 5). Then, for all of these structures the aerial image generated in the EUV lithography step is computed with the rigorous lithography simulator Dr.LiTHO of IISB (Fig. 6). This data set consisting of mask inputs and corresponding aerial images is then used to train the neural network. The trained network can then be used to decide for a measured SEM picture whether the mask feature is defective or not, and to classify the kind of defect. Furthermore, the use of a neural network especially tailored for this application by IISB resulted in a reduction of the training time by about a factor of ten compared to general-purpose neural networks reported as efficient in the literature, whereas the accuracy of the trained network was even slightly increased. In the next step, Dr.LiTHO is also used to assess the so-called "process window" for the defective structure, which is the range of the process parameters focus and threshold for which the printed feature size ("critical dimension" CD) does not deviate from its nominal value by more than 10 % (Fig. 7). The parabolic lines represent the certain values for the CDs in horizontal and vertical direction. Black lines represent the CD without defect and the red lines with defect. Upper lines are for nominal CD plus 10 %, lower lines for nominal CD minus 10 %. The yellow area represents the common process window where both horizontal and vertical feature sizes are within the 10 % specification both without and with defect.

The other extreme of the application window addressed at IISB deals with the optimization of power electronic systems. For this area, it is frequently not sufficient to combine TCAD tools,

MODELING AND ARTIFICIAL INTELLIGENCE

Physics and Artificial Intelligence: No Competitors but Together Ever More Useful
Design Automation in Power Electronics: Workflow and AI



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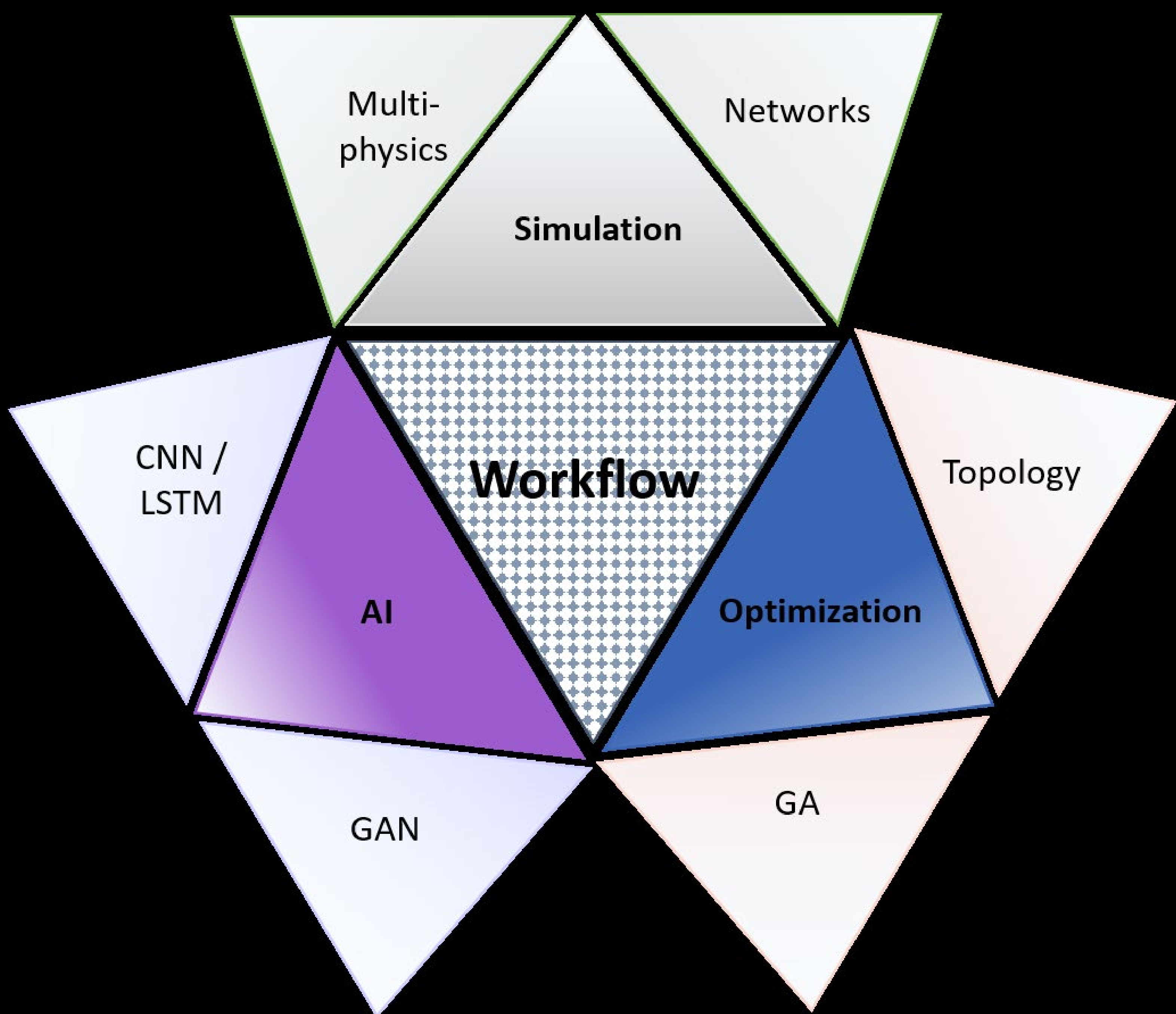

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such as process and device simulation, with AI approaches: The diverse nature of the active and passive components used, the various physical effects to be addressed, including electrical, mechanical, thermal, and reliability properties, and the need to include cost aspects require a more sophisticated workflow combining multiphysics simulation with powerful global optimization. The following subchapter on "design automation in power electronics" deals with this aspect.

DESIGN AUTOMATION IN POWER ELECTRONICS: WORKFLOW AND AI

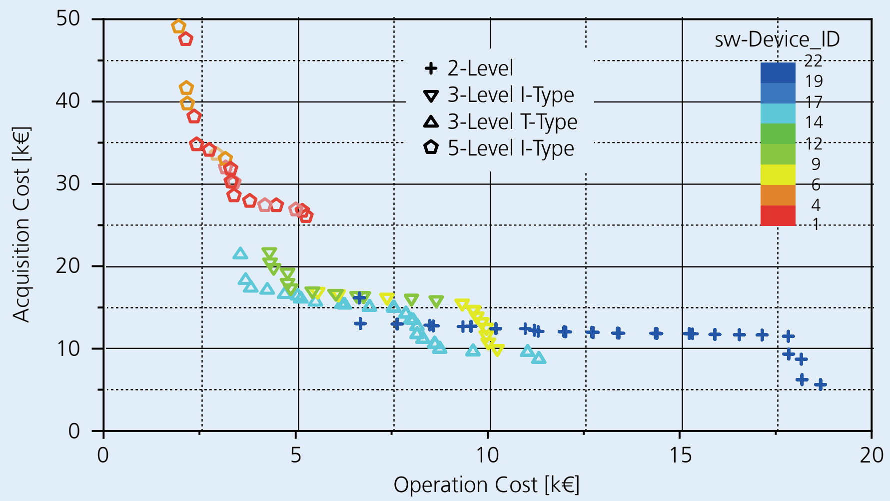
In the development process for power electronic components and systems one of the dominating time and cost factors is the design of prototypes. This results from the large number of assembling, manufacturing, and verifying processes required for a functional product, and calls for innovative approaches to drastically increase efficiency in the workflow. Even though a wide bunch of software tools provides solutions for all kinds of simulation, data storage, and analysis as well as visualization and reporting, an automated software pipeline for a simulation based product development is still lacking. Consequently, an increasing international community of domain and simulation experts addresses this topic gathered under the term of "Design Automation in Power Electronics".

Technological domain knowledge and simulation combined at IISB

At IISB, the interaction of experts on power electronic systems and simulation specialists was already during the LZE (Leistungszentrum Elektroniksysteme) project driving the design of inductive components. It has been brought to a new level during the two last years by designing a new software framework in the group "AI-Augmented Simulation". The open-source python-based framework has a modular structure (see Fig. 8) and provides workflow functionality for a parallel execution on different computational hardware (CPU, Cloud and Cluster), license, and resource management as well as an advanced multi-objective optimization strategy. Up to now, several separate software modules are designed enabling interactions with different software tools (Ansys Q3D, SigmaET, FEMM, LTSpice, etc.). Based on these modules, customized workflows can be set up and evaluated within the framework. Due to the modular implementation, a fast adaption on varying use cases and the interaction of multiple software tools and programs can be realized. Exemplarily, geometries are automatically generated in a CAD program and afterwards transferred to an electromagnetic analysis and a fluid simulation in parallel, while the

8 *Schematic workflow for design automation, including Convolution Neural Networks (CNN), Long Short Term Memory Networks (LSTM), Generative Adversial Networks (GAN) and Genetic Algorithms (GAs).*

9 *Example for optimization of inductive systems concerning space and losses.*



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results are combined for determining a Pareto optimum. Within such a scenario, sophisticated scheduling strategy for the different modules is crucial for reaching a highly efficient use of the resources, taking into account the CPU, memory, and license load: The targeted and achieved average efficiency is more than 90 % on multi-core processors.

Workflow approach

Especially for typical power electronic design cases, the number of degrees of freedom leads to a large amount of simulation tasks, which need to be carried out efficiently. One typical application case is to find the inductive component or system with minimal losses for a defined installation space (length, width, and height of the system) and specific construction parameters (number of windings, diameter of coils, etc.) including a choice from a variety of different materials and electric components. Moreover, the losses should represent a realistic usage scenario and therefore require the calculation for multiple operating points. Within the optimization process, a few setups based on a randomized parameter selection are used to get the first initial components and corresponding simulation results. Based on this first generation, representative fitness values are calculated and used for rating the designs within the evolutionary optimization strategy of the genetic optimizer employed. The expediency of the underlying fitness function can be enhanced by implementing domain system knowledge through rating and weighting the output results. The performance of the evolutionary optimization crucially depends on the mating and mutation strategy applied on the parameter pool. A clever and adaptable strategy will provide iteratively generations of setups with an increasingly better performance in terms of power losses. After some thousands of evaluation loops and achieving convergence, system proposals will be available, which have the minimal power loss while still satisfying the initially specified criterions.

Application examples

This procedure has already been demonstrated in minimizing the power losses of coil systems in the domain of inductive power transfer (see Fig. 9), in the design of efficient (considering drag drop versus power transfer) pin fin structures and in the circuit design. It is this latter item in particular which provides a high potential for design automation in power electronics: Based on a defined netlist structure of an electric circuit, multiple parameter values have to be tuned to achieve a defined performance. The highly non-linear system behavior combined with multiple minimization objectives is very challenging and pushes even the best experts to their limits. Within our optimization framework, several millions of circuit evaluations are performed in one day providing tailored solutions for most of the circuit problems.

One example deals with the multiobjective optimization of the topology and the devices used in a converter regarding its required electrical properties (which were treated as constraints), the costs of production /acquisition, and the costs of operation. Here, a set of circuit simulations has been used to train neural networks for a wide set of converter topologies and devices (see Table) to be investigated. Several Genetic Algorithms are then employed, which compete in the search of the global optimum. Since the reduction of acquisition and of operating costs are partly competing targets, for each converter topology a Pareto plot for the optimum values in the acquisition costs / operation costs space is found, see Fig. 10. Within the front the characteristics of the devices used in the inverter change, as indicated in the colour code. This is an example how the workflow of physical simulation tools and Neural Networks can be combined with advanced optimization approaches and domain knowledge to assess and approach the technological limits.

Device_ID	VCES	Configuration	IC
1	1700.0	Dual	400.0
2	1700.0	Single	1200.0
3	1700.0	Single	1600.0
…			
4	6500.0	Single	750.0

Device_ID	VRRM	Configuration	IF
23	1800.0	Dual Diode	1200.0
24	1800.0	Dual Diode	900.0
…			
30	4500.0	Dual Diode	400.0

10 *Pareto front resulting from the optimization of a power electronic circuit with regard to acquisition (production) and operation costs for four different circuit topologies (symbols) and using different devices (colour scale).*

11 *Table „Device technology": Example for list of devices used in optimization of Fig 10.*

Future work

Based on the experience made regarding the capabilities and performance of the framework, and on the domain knowledge of IISB in power electronics, current work focuses on the further enhancement of the performance and user friendliness of the software and its demonstration and where needed extension for a wide set of use cases in power electronics.

Contact

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MATERIALS

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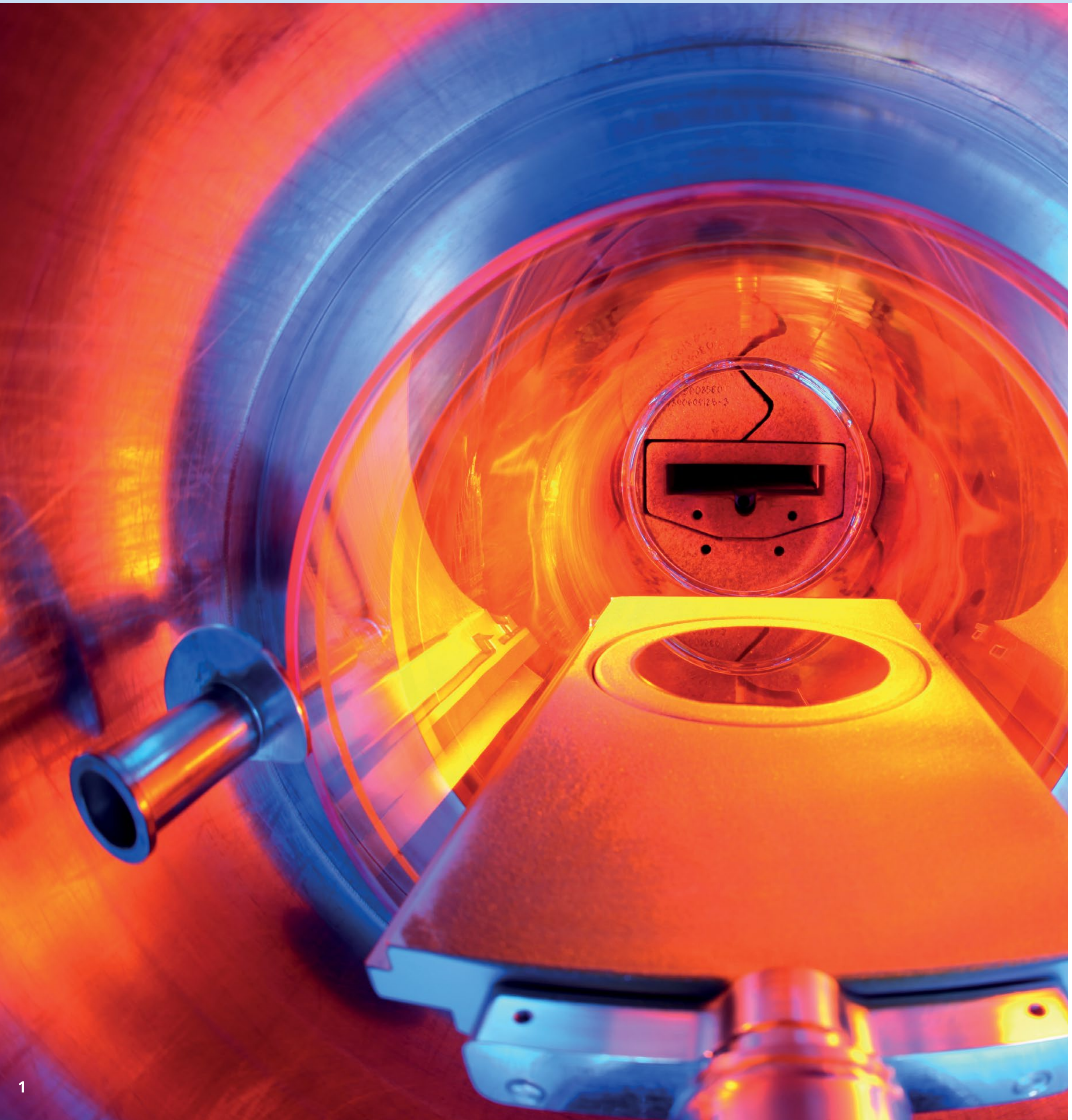

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Our mission

We support material, device, and equipment manufacturers and their suppliers by delivering scientific-technological solutions in the field of production and characterization of crystals, epitaxial layers, and devices. For that purpose, we develop and improve equipment, processing, modelling, and characterization techniques. Our main focus is on semiconductors, but we are also experienced with optical, laser, and scintillator crystals. We pioneer novel ultra-wide band gap, quantum, and battery materials. Our customers' benefits are new products at reduced costs, higher yield, better quality, and improved device reliability.

Our strategy

Our strategy is the optimization of the manufacturing processes through a combination of thorough experimental process analysis, tailored characterization techniques, and numerical modeling. For that purpose, we have a well-suited infrastructure at hand, which consists of R&D type furnaces and epitaxial reactors, state-of-the-art-metrology tools for the investigation of the physical, chemical, electrical, and structural material properties as well as powerful simulation programs well suited for heat and mass transport calculations in high temperature equipment.

Main areas

Silicon: We perform specific research on growth of silicon by the Czochralski technique mainly for power electronics and photovoltaics application with respect to higher yield and improved material quality. In the field of directional solidification, emphasis is put on innovative crucible and coating materials to reduce harmful defects and impurities. Numerical modeling gives us a deeper insight into the heat and mass transport phenomena occurring during growth. We offer individual services such as specific crystal growth experiments and characterization of silicon.

Silicon Carbide & Diamond: We develop the SiC epitaxy process with emphasis on improved material quality. State-of-the-art metrology tools such as UV-PL or XRT together with the possibility to process complete devices allow us to correlate the properties of the epilayer and the substrate with electrical device parameters. Based on these findings solutions are demonstrated how to overcome harmful defects. In addition, the potential of SiC and diamond for quantum applications is explored. In this area we investigate especially how color centers in SiC and diamond can be generated.

GaN & AlN: We develop the HVPE growth of GaN crystals. The process is optimized towards a high uniform V/III ratio along the growing interface by comparing in-situ process data, ex-situ determined properties of the crystal with results from numerical modeling of the growth process.

1 *View into horizontal hot-wall reactor for SiC homoepitaxy during wafer loading.*
© Kurt Fuchs / Fraunhofer IISB

2 *Dr. Jochen Friedrich, head of the Materials department.*
© Kurt Fuchs / Fraunhofer IISB

MATERIALS

Innovative Reliable Nitride-based Power Devices and Applications: The EU-Project Inrel-Npower

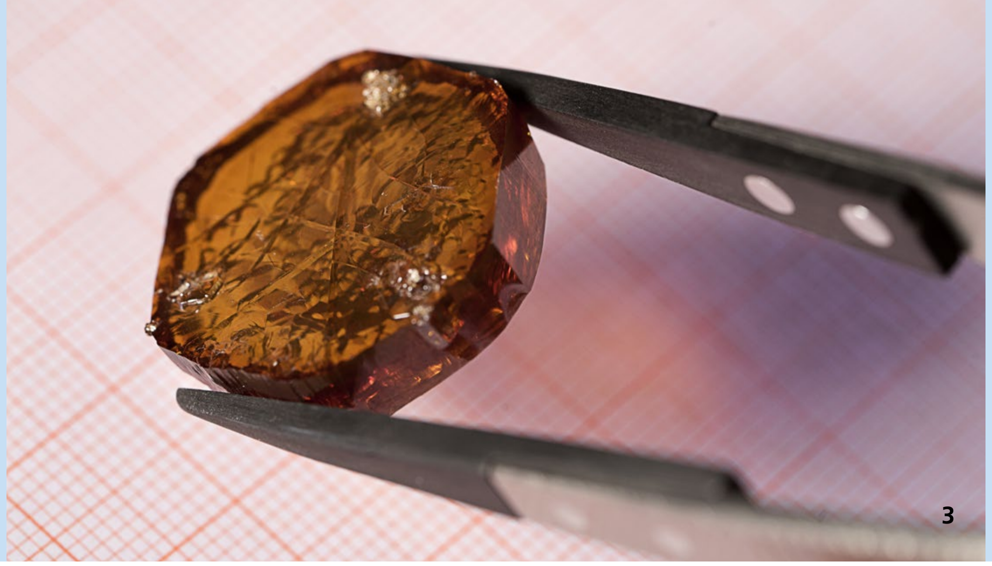
We pioneer the PVT growth of AlN crystals with the focus of deeper understanding of growth mechanisms and upscaling towards larger crystal diameters. In our wafering line we explore advanced GaN and AlN crystal preparation and characterization technologies for epi-ready wafers.

Other Crystal Materials: We are well experienced in the growth and characterization of a variety of other semiconductor materials (Ge, GaAs, InP, CdTe) as well as of optical, laser, and scintillator crystals (sapphire, oxides (LSO, YVO4, Y2O3) or halides (CaF2, CeBr3)) by different melt and solution growth techniques. We support our customers in the development of new crystal growth and epitaxy equipment and processes based on our broad material expertise and by using numerical simulation. Furthermore, we offer specific characterization services of crystal and wafer material.

Material qualification & test devices: We are experienced with the characterization of the electrical, structural, physical, and chemical properties of different crystal, wafer, and epi materials. This includes, e.g., specific techniques like x-ray topography, various atomic force microscopy methods, and electrical and optical defect spectroscopy. Furthermore, we utilize a customized design of test devices, which are processed in a fully CMOS equipped cleanroom facility. This allows a systematic correlation of the material properties to device performance and the identification of device critical defects.

Energy Materials: We analyze rechargeable aluminum-ion battery systems as future long-term alternative of lithium-ion batteries. Therefore, we develop new cathode materials and electrolytes. The materials are assembled into battery test cells and characterized with respect to their electrochemical behavior. Furthermore, we develop technologies to recycle silicon from sawing waste and to reuse the recycled silicon for thermoelectric generators, as anode material for lithium batteries, and for precursors for 3D printing of high strength, lightweight AlSi alloys.

Equipment Simulation: We support the development of high-temperature equipment and processes by our expertise in numerical modeling of the heat and mass transport phenomena. Specific expertise is available for crystal growth and epitaxial processes. But we are also experienced with thermal treatment of wafers and CVD applications. We provide solutions for furnace modifications in order to optimize the process equipment and we give new insights into the processes, especially for parameters that are hardly accessible via measuring techniques like species distributions or convection pattern.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3 *AlN-Crystal with 1 inch diameter grown by the PVT method at IISB. © Anja Grabinger / Fraunhofer IISB*

INNOVATIVE RELIABLE NITRIDE-BASED POWER DEVICES AND APPLICATIONS: THE EU PROJECT INREL-NPOWER

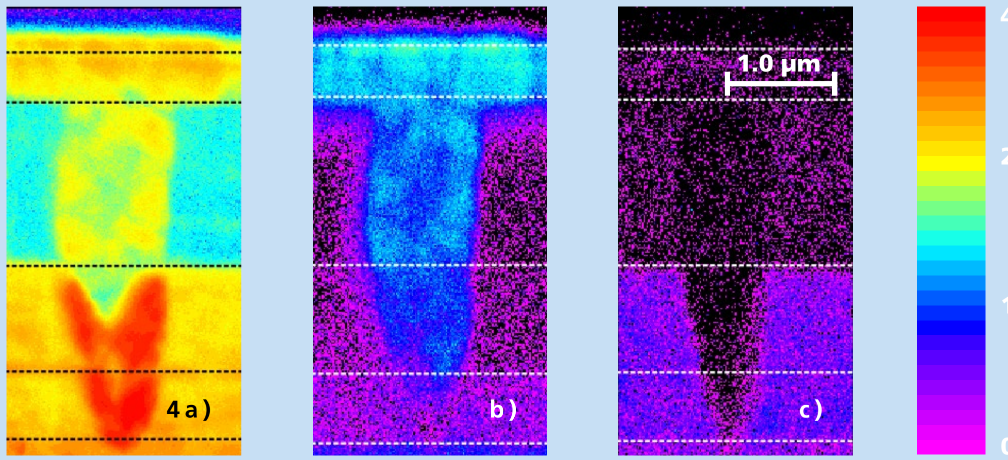
Conversion of electric energy is currently highly inefficient to the point that only around 20 % of the whole energy involved in energy generation reaches the end-user. Wide bandgap semiconductors like SiC, GaN, AlN, or diamond and devices based on those materials exhibit unique characteristics like high maximum current, high breakdown voltage and high switching frequency as compared to Si and are therefore the materials of choice for solving future energy problems. The partners within the EU-project InRel-NPower aim for the development of robust and reliable GaN- and AlN-based power devices. Within this project, Fraunhofer IISB investigates the role of material characteristics like certain defects on device performance and reliability.

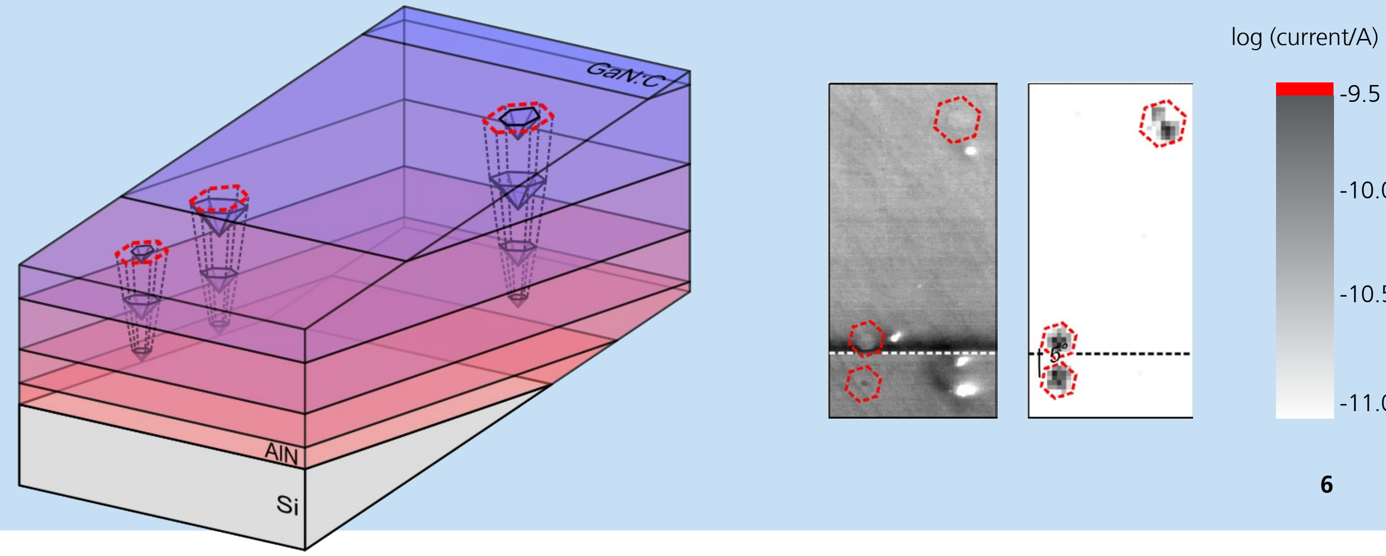
GaN on Si power devices

Quality and homogeneity of semiconductor wafers are crucial for devices processed on top. Nowadays, commercially available free-standing GaN-wafers have a diameter of typically 2 inches and exhibit a dislocation density of 10^6 cm^{-2} at a prize of around 1 - 2 k€. These scales and costs motivate the heteroepitaxial growth of GaN on Si. The device of choice is the AlGaN/GaN high electron mobility transistor (HEMT), which is realized by growing a 20 nm thin AlGaN layer with an AlN mole fraction of 0.25 on top of the GaN layer. The great advantage of such a device is the intrinsic presence of a highly conductive transistor channel in terms of a two dimensional electron gas (2DEG), which forms at the AlGaN/GaN interface as a consequence of the materials' different internal polarizations. However, crystal lattice parameters and thermal expansion coefficients of GaN and Si differ significantly, which requires advanced strain-engineering techniques by growing a multi-layer stack between AlGaN/GaN and Si. Still, a large amount of defects like dislocations in the order of 10^9 cm^{-2} remains in the material. It is yet unknown how these defects will impact performance and reliability of power devices, which is a major concern for wide-spread market adoption.

How V-pits limit the device breakdown

Growth of GaN on Si typically starts with an AlN nucleation layer. The surface of this layer is commonly covered by so called V-pits due to a 3D growth mode. Consecutive layers are grown on top of this surface and can be assumed to have material characteristics that depend on density and size of such V-pits. Fraunhofer IISB was able to directly reveal one dominant impact of V-pits on power device structures and to develop more robust devices together with its project partners by adapting growth parameters of the nucleation layer.



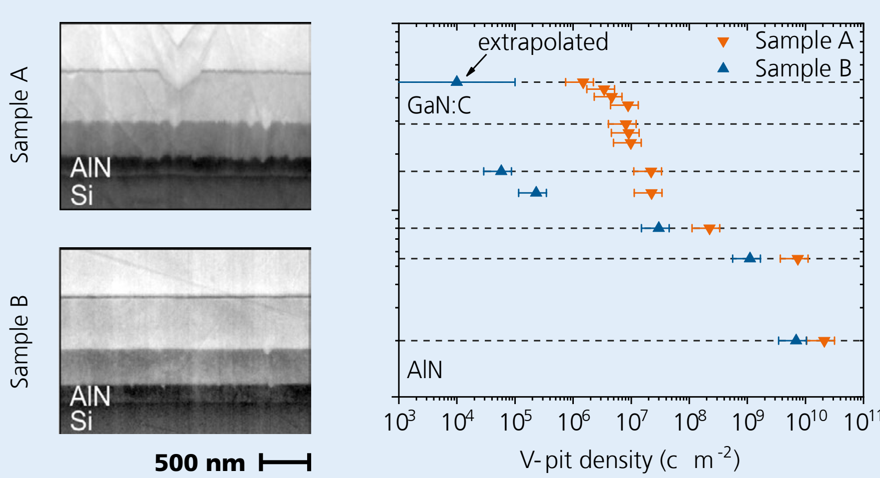


Different samples have been investigated with regard to the presence of V-pits in the multi-layer structure by cross-sectioning and the fabrication of slanted samples. It turned out that not only the presence of V-pits within the nucleation layer itself, but also the efficiency of over-growth in the layers above is strongly dependent on nucleation layer growth conditions (see Fig. 5).

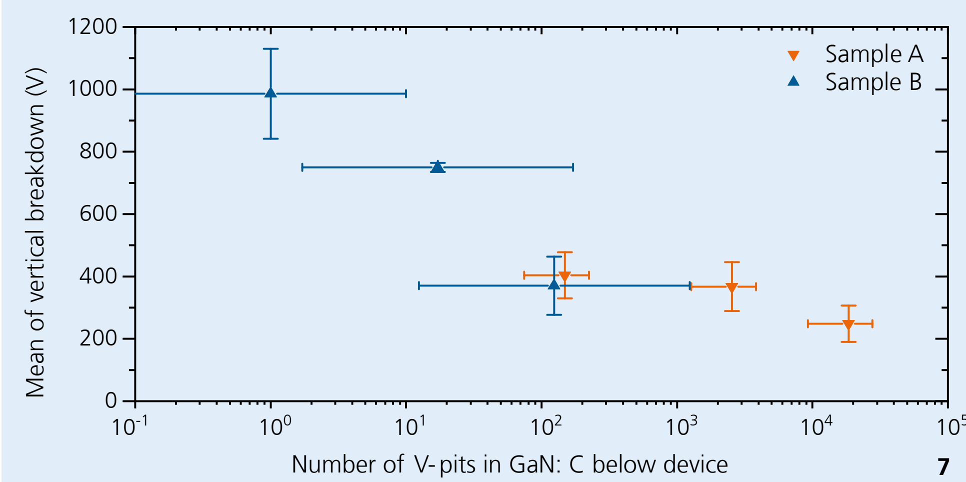
A depth-resolved analysis of crystalline impurities by Secondary Ion Mass Spectrometry showed a significant statistical correlation between the presence of V-pits and an increased/decreased concentration of O/C. This relation was also directly probed by cross-sectional Cathodoluminescence investigations (see Fig. 4). Not only the luminescence was greatly enhanced within the overgrown region of V-pits, but also its dependence on temperature, which was found to be indicative for the local presence of defect centers involving O, vacancies or V-impurity complexes.

As O is a shallow donor and C a deep acceptor in n-type AlGaN and GaN, a highly increased electrical conductivity at V-pit sites was supposed. This hypothesis was directly proven by measuring the vertical leakage current through the material on a sub-µm scale and comparing the appearance of leakage spots to the location of V-pits within the material, which gave a one-to-one correlation (see Fig. 6).

The meaning of these findings for devices was statistically evaluated. Vertical breakdown voltage was measured on different devices for different samples and compared to the amount of V-pits that are statistically expected within the highly insulating C-doped GaN-layer of the layer stack below the devices. The result was a common relationship for all measurements, that is a logarithmic dependence of breakdown on the amount of V-pits (see Fig. 7).



Moreover, the study showed a vertical breakdown limitation of typical GaN on Si HEMT structures due to other defects like dislocations by extrapolating the found relationship to zero V-pits below the device.



The role of dislocations

Like V-pits, dislocations in GaN on Si HEMT structures emerge from the AlN nucleation layer. In contrast to V-pits, they are able to penetrate the whole layer stack and reach the wafer surface. The role of dislocations with regard to device reliability is widely discussed, but still hardly understood due to the big challenge to experimentally address open questions.

Within InRel-NPower, Fraunhofer IISB developed an innovative characterization methodology to investigate the electrical properties of single dislocations. Without any processing being necessary, this allowed to map leakage paths through the topmost AlGaN layer only, which is especially relevant for transistor gate characteristics, and to demonstrate why present results in literature are widely spread and seem to be diverse.

Mapping of microscopic leakage paths on different samples was carried out by using an Atomic Force Microscopy and applying a bias between Si and the AFM tip (C-AFM). A typical result obtained for GaN on Si HEMT structures exhibits a large density of discrete leakage spots (see Fig. 8).

4 *Panchromatic and monochromatic Cathodoluminescence mappings of a V-pit in cross-section:*
a) *Panchromatic CL*
b) *GaN NBE*
c) *BL*

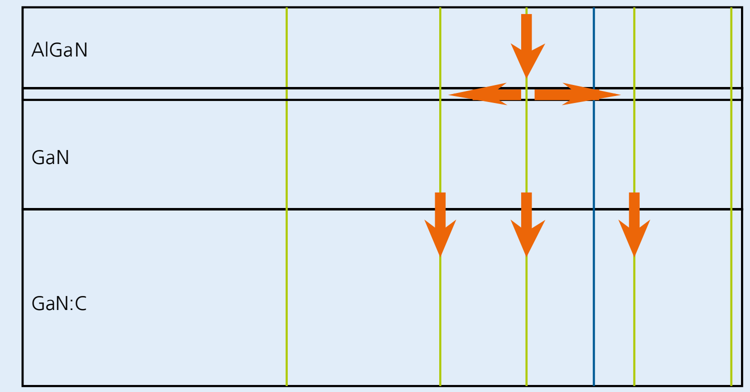
5 *Scanning Electron Microscopy images showing V-pits in cross-section and development of the V-pit diameters in dependence of vertical position within the layer stack.*

6 *C-AFM measurement showing the correlation between local leakage current paths and V-pits.*

7 *Logarithmic dependence of the vertical breakdown on the amount of V-pits below the device within the C-doped GaN-layer.*

MATERIALS

Innovative Reliable Nitride-based Power Devices and Applications: The EU-Project Inrel-Npower



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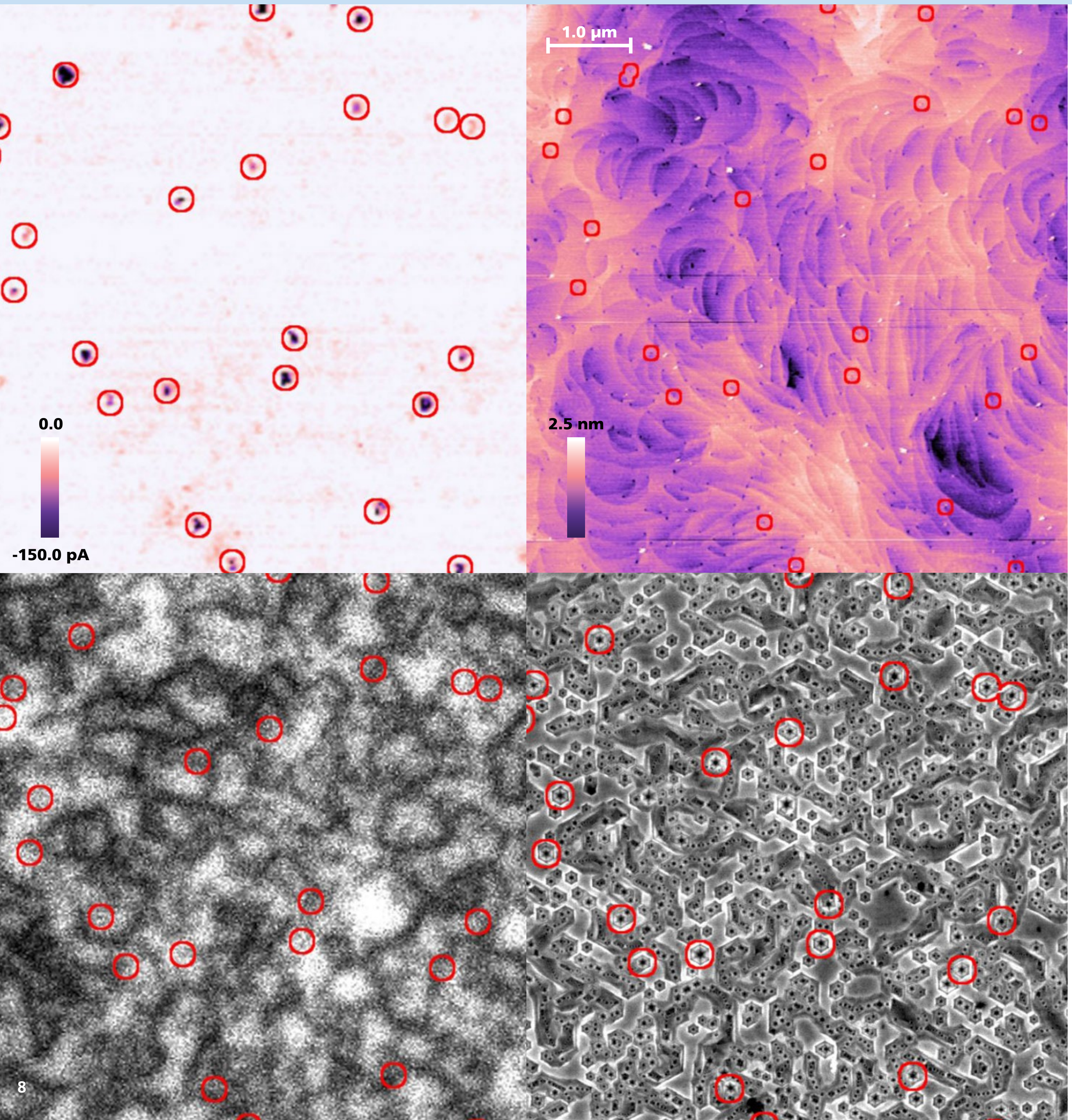

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A direct correlation to the sample topography measured by AFM, the full underlying dislocation structure measured by Cathodoluminescence and the etch pit distribution and geometry after defect selective etching showed that first only a portion of dislocations is able to conduct current within the detection limit of the setup and second that only dislocations with screw component are candidates for that, but never dislocations of pure edge type (see Fig. 8).

The portion of dislocations with a screw component and therefore the total amount of conductive dislocations was found to be characteristic for the growth process.

A comparison of some tailored samples and of C-AFM measurements in a lateral bias configuration could show that observed leakage spots represent leakage paths through the topmost AlGaN layer and are not necessarily leakage paths that penetrate all the way down to Si. The reason for this is the shunting of all layers below the 2DEG due to its high lateral conductivity (see Fig. 9).

The specific role of single dislocations in terms of gate characteristics is work in progress and something to be investigated in the last year of the project.

Conclusion

The results achieved within the project InRel-NPower enabled the partners to develop AlGaN/GaN HEMTs based on Si- and AlN-substrates that do not only show a significantly enhanced device breakdown capability, but also a greatly improved dynamic behaviour by developing advanced multi-layer stack designs.

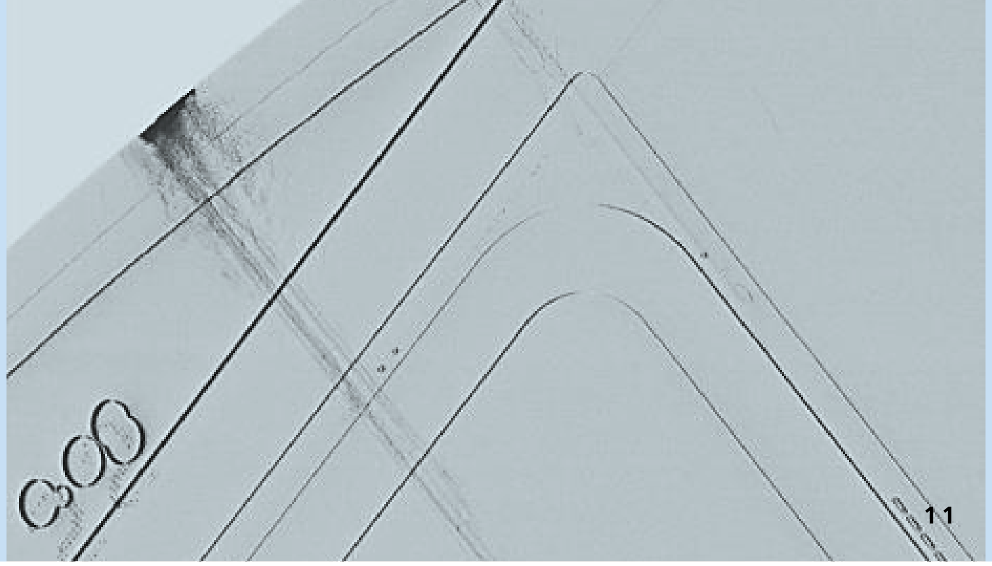
This was accomplished by a close collaboration between partners from the material, device, and application site both from academic and industrial institutions.

8 *Correlation of C-AFM, AFM, Cathodoluminescence and defect selective etching on an identical area.*

9 *Draft of the dislocation-related leakage current flow in vertical direction.*

MATERIALS

Advanced X-Ray Topography Imaging



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ADVANCED X-RAY TOPOGRAPHY IMAGING

Characterization of structural defects in semiconductor materials is an important task to understand the influence of the production conditions on the material quality of substrates and epilayers and to correlate the impact of structural defects on the performance and reliability of devices manufactured out of the substrates and epilayers.

In the frame of Research Fab Microelectronics Germany (FMD) IISB has installed a unique X-ray topography tool (see Fig. 10). The XRTmicron gives the possibility to investigate crystallographic defects with high speed and highest resolution on full wafer scale.

It is well suited for bare wafers, wafers with epilayer structures, partially processed wafers as well as bonded wafers. The amount and different types of dislocations, slip lines, dislocation networks, (small angle) grain boundaries, inclusions, precipitates, pits, scratches, stress level, etc. can be imaged and quantified on the samples. These features pushes Fraunhofer IISB on a leading position in the area of non-destructive defect characterization in semiconductor wafers of industrial relevance.

Tool features and benefits

- Non-destructive imaging of defects for samples up to 300 mm in diameter
- Materials: Si, Ge, Diamond, SiC, GaN, AlN, GaAs, InP, CdTe, Al_2O_3, etc.
- Dual wavelength X-ray source (Mo and Cu) in transmission and reflection geometry
- Imaging by two high resolution cameras with 5.4 and 2.4 µm per pixel
- Cross section topography and 3D reconstruction of defects in the volume

Typical application examples

After intensive performance tests of the equipment, numerous measurements for industrial clients were performed. For instance, glide plane distributions in a processed 200 mm silicon wafer can be unambiguously made visible indicating at which position on the wafer device failure can be expected (see Fig. 11).

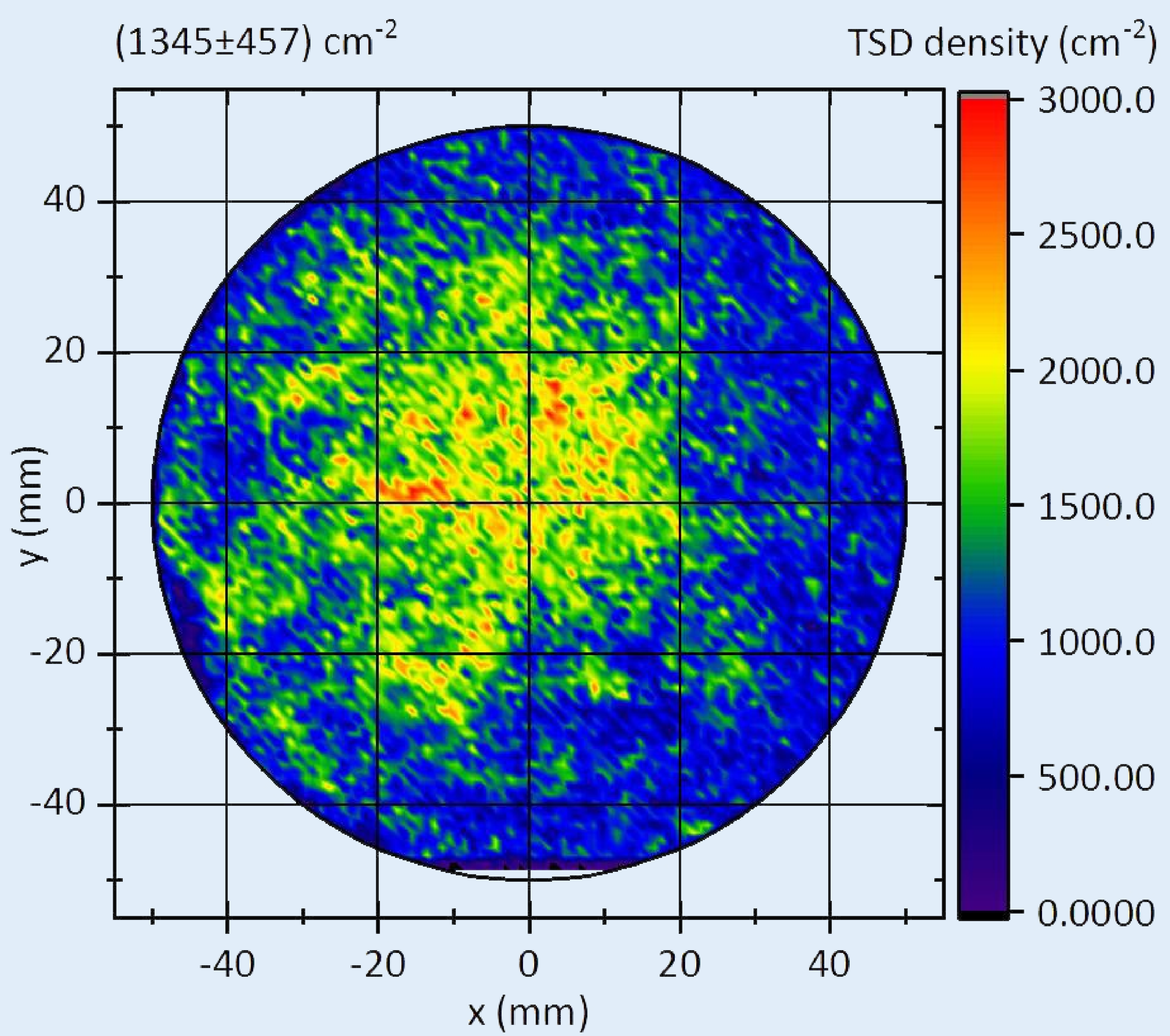
The main focus was in the development of measurement routines and subsequent quantitative analysis of threading screw dislocations (TSD) of 4H-SiC wafers with diameters up to 150 mm.

10 *XRTmicron at Fraunhofer IISB.*
© Kurt Fuchs / Fraunhofer IISB

11 *Glide planes on a 200 mm processed silicon wafer.*

MATERIALS

Advanced X-Ray Topography Imaging



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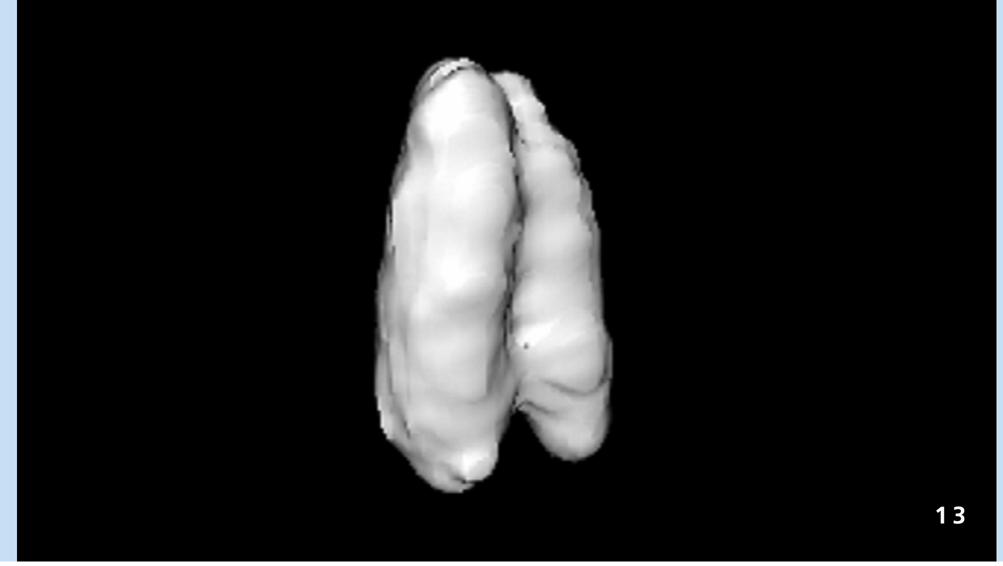

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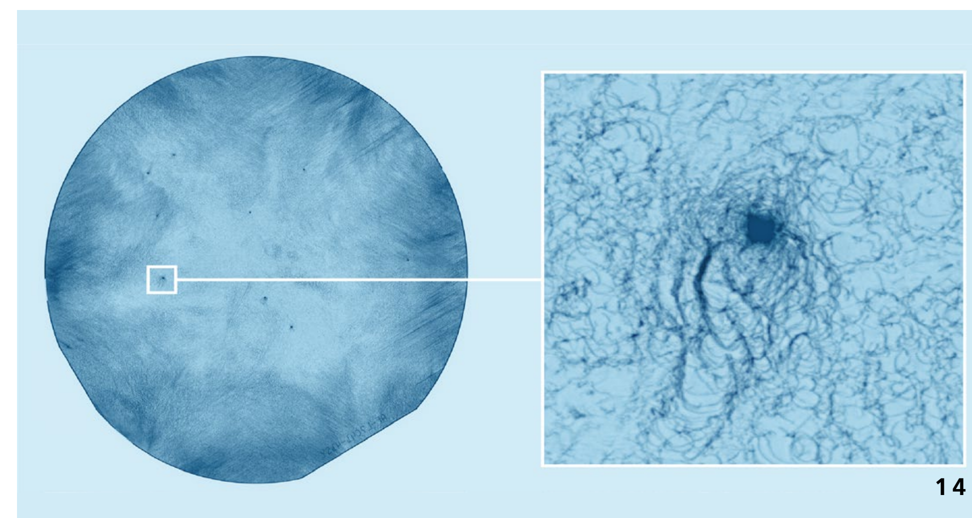
Fig. 14 shows a typical topograph and Fig. 12 the respective TSD density map. These maps serve as valuable feedback information for the substrate supplier in order to ensure the quality of the growth process. Also it allows in the device processing predicting the device yield by measuring the defect distribution before and after homoepitaxy.



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In addition, measurement routines for cross-sectional topography inside the wafer volume with respect to three-dimensional defect reconstruction have been established. Exemplarily, a triangle defect in a 4H-SiC homoepitaxial layer is visualized in Fig. 13 which acts as a killing defect in subsequent device fabrication.

Finally, the XRT tool is extensively used for other materials like AlN and GaN crystals and substrates, Ge or Sapphire.

Contact

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12 *Quantitative analysis of the Threading Screw dislocation density (TSD) of the 4H-SiC wafer in figure 14.*

13 *Three-dimensional reconstruction of the triangle defect in 4H-SiC homo-epitaxial layer by cross sectional XRT measurement.*

14 *XRT topograph of a 100 mm 4H-SiC wafer (left) with enlargement of the center.*

TECHNOLOGY AND MANUFACTURING

2

1

Technology and manufacturing at Fraunhofer IISB mean above all research, development, and prototype manufacturing in the field of power electronic devices on silicon (Si) as well as on 4H-silicon carbide (SiC). In particular the service sector is set up in a separate organizational unit called π-Fab, to meet the requirements of our external and internal customers better. π-Fab is intended for the fabrication of custom-tailored prototype electron devices, mainly for power electronic application, and it is ISO 9001:2015 certificated for this. For this purpose, IISB and the Chair of Electron Devices of the University of Erlangen-Nürnberg operate joint cleanroom facilities of 1500 m^2 (primarily class 10) with CMOS-compatible equipment. This allows the implementation of important process steps on silicon wafers with diameters of up to 200 mm and on SiC wafers with diameters of up to 150 mm. An industrial CMOS process transferred to IISB and constantly adapted for research and development purposes is used as a reference and as the basis for developing advanced process technologies.

The main activities focus on the fields of Si power semiconductors, passives, and silicon carbide electronics. IISB has increased its commitment especially to SiC by implementing new equipment and processes to meet special and additional requirements for SiC power device processing. The main part of the FMD (Forschungsfabrik Mikroelektronik Deutschland – "Research Fab Microelectronics Germany") investments of the Technology and Manufacturing department are dedicated to the change in wafer size on SiC from 100 mm to 150 mm. This above all concerns the etching and refilling of deep trenches and the high-temperature processing of SiC. Furthermore, the FMD investment allows us to broaden our process portfolio by providing backside grinding and polishing for SiC wafer thinning and providing laser annealing for backside ohmic contact formation on the front side of already processed wafers. As a result, industrially competitive low ohmic contact can be provided. All of this allows the department to strengthen its competence in manufacturing high-voltage power devices. By now, IISB has developed its resources and expertise to the point where it can perform nearly all manufacturing steps on SiC substrates according to an industrial standard. The devices currently under development include diodes and merged pin diodes in the voltage ranges from 1.2 kV up to 4.5 kV, as well as MOSFET devices such as vertical or lateral DMOS. A trench technology for vertical diodes and MOSFET as well as sensor and high-temperature CMOS devices are in progress. For the development of novel process steps in the field of dielectrics and metallization, IISB operates advanced sputter and chemical vapor deposition tools on the basis of ALD that are used for the deposition of high-k and metallic layers.

Furthermore, special activities focus on ion implantation technologies. At IISB, implantation tools with acceleration voltages ranging from a few eV up to 800 keV are available. Special implantations for CMOS as well as for power semi-conductors have been established (for example, commercial tools have been modified to be able to implant several wafer diameters and manifold elements at elevated temperatures). The physical and electrical characterization of process steps and device structures is of the utmost importance for the manufacturing of semiconductor devic-

1 *Debonding of 100 µm thinned 150 mm SiC device wafer.*
© Kurt Fuchs / Fraunhofer IISB

2 *Dr. Anton Bauer, head of the Technology and Manufacturing department.*
© Kurt Fuchs / Fraunhofer IISB

TECHNOLOGY AND MANUFACTURING

Adaptive Sampling and Contamination Control Methods for Silicon and SiC Manufacturing Lines and their Supply Chains

es. Important steps in this respect are the determination of the topography, doping profile, and further physical and chemical parameters, as well as FIB investigations, energy-dispersive X-ray analysis, and AFM surface characterization of layers. A specific competence of the department is the combination of several methods for failure analysis during the processing of semiconductor devices and tracing the causes of failures. The spectrum for electrical characterization has been further increased (e.g., lifetime measurements and high-voltage measurements especially for SiC). Furthermore, from nanotechnology to printable macro-electronics, the Technology and Manufacturing department is your contact for the realization and characterization of single process steps up to prototype devices.

Based on comprehensive cleanroom facilities, further activities are becoming more and more relevant. An example of such current activities is low-temperature deposition of inorganic materials using printing techniques. The emerging markets for such products are control units and specific sensors based on inorganic materials. The field of thin-film systems ranges from materials to device exploration to the development of TOLAE (thin, organic, and large-area electronics) applications. Based on a carefully targeted selection from solution processing/printing, spray coating, or vapor deposition of inorganic layers, the devices are optimized for their respective environment. Printed electrolyte sensors integrated with read-out and data handling electronics allow physical strain to be monitored in wearable sports trackers and can also be utilized in the chemical industry, water quality assessment, or several agricultural tasks. Capacitive and temperature sensing in combination with high performance TFTs enable the realization of smart integrated thin-film systems. Another focal area of the department's work is the processing of structures in the range of a few nanometers as well as the repair and analysis of electronic device prototypes by means of focused ion beam (FIB) techniques and electron beams. In addition to that, UV nano-imprint lithography, a cost-effective fabrication technique that allows the transfer of nano-sized features to photo-resist without the use of advanced optical lithography by applying small rigid stamps and, most importantly, by applying large-area (up to 150 mm) flexible stamps too, is now well established. A core competence of the Manufacturing Control group is contamination control in advanced CMOS processing. The IISB analysis laboratory for micro and nanotechnology with various chemical, physical-chemical, and physical test methods is essential for a conclusive and comprehensible assessment.

Several working groups at Fraunhofer IISB contribute their expertise in Advanced Process Control, manufacturing science, productivity, contamination control, and yield control aspects to the running ECSEL projects "Productive4.0" and "iDev40". With 109 partners involved, Productive4.0 is Europe's biggest research project in the field of Digital Industry. By interlinking development processes, logistics, and production with Industry 4.0 technologies, iDev40 achieves a disruptive step towards speedup in time to market.

3 *Sample preparation for contamination control by ion chromatography © Kurt Fuchs / Fraunhofer IISB*

ADAPTIVE SAMPLING AND CONTAMINATION CONTROL METHODS FOR SILICON AND SIC MANUFACTURING LINES AND THEIR SUPPLY CHAINS

From the very beginning, Fraunhofer IISB has been working on methods for the control of ultra-clean manufacturing processes and ultra-trace analysis. Typical applications of these methods are the contamination control of manufacturing processes including the corresponding equipment and process media as well as the control of manufacturing environments (e.g., cleanroom, minienvironments) including the evaluation of cleanroom filters and filter materials in general. With feature sizes shrinking, thinner layers, new materials, 3D integration, thin wafer technologies, and more complex designs, contamination control is a constant challenge and a prerequisite for a continuous quality control and achieving high yields in the manufacturing processes. Recently, microcontamination control has become a very hot topic, as it has been shown that microcontamination, while not affecting yield, can affect the long-term reliability of a chip. This can be a major problem, especially in automotive applications such as autonomous driving.

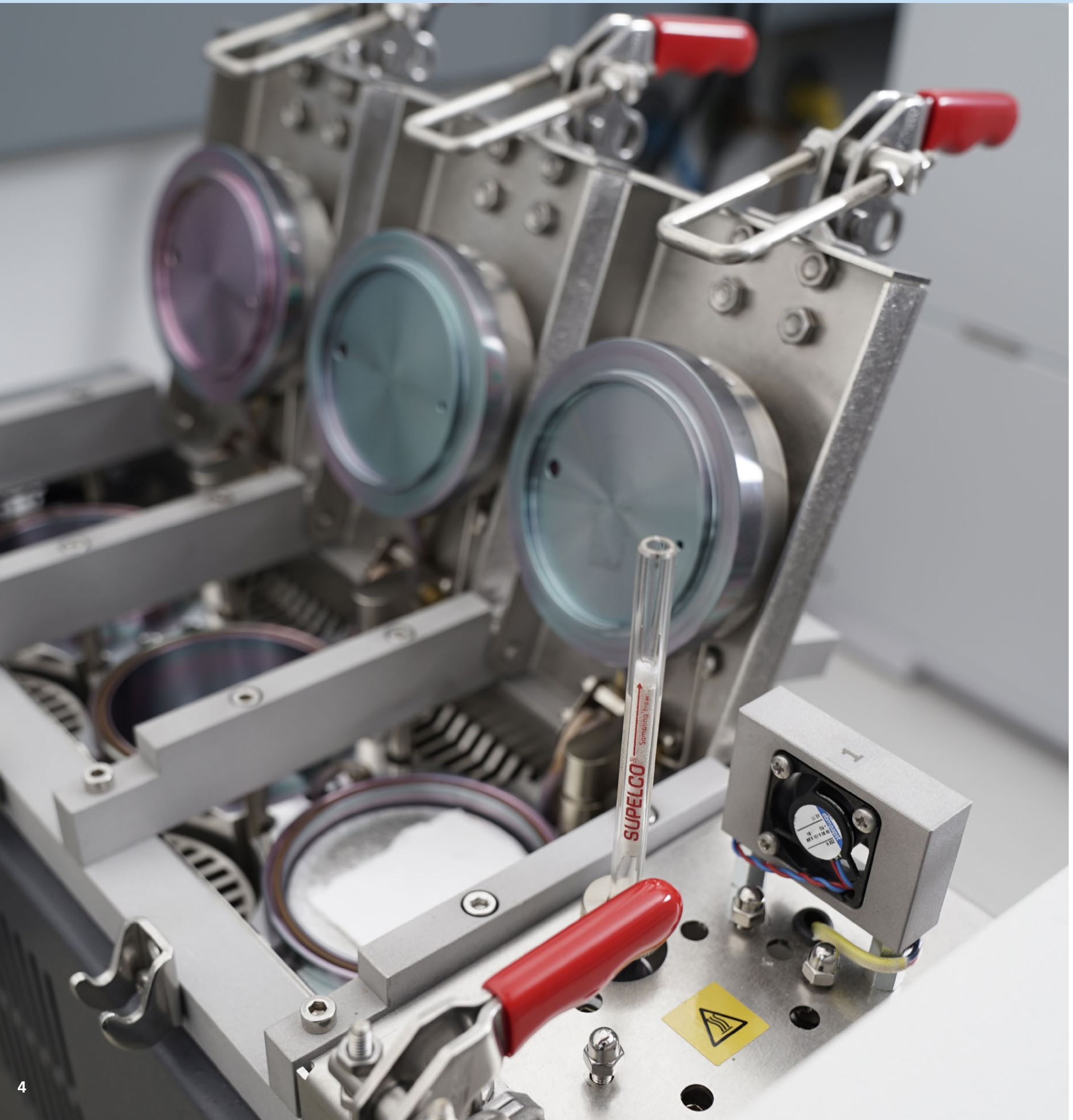
With the establishment of the π-Fab – a prototyping service which comprises a continuous silicon CMOS and silicon carbide process line in an industry-compatible environment – and its ISO 9001 certification, contamination control procedures also became a must in a variety of internal processes, like equipment qualification / requalification and continuous quality control.

The focus of equipment development and assessment projects is to quantify the contamination behavior of the equipment, to determine contamination sources, and to certify the cleanroom suitability. Usually outgassing tests of equipment components and used material are common during the deployment phase. Therefore, different collection and extraction methods are being utilized and adapted, respectively.

Based on many years of experience and profound knowledge of the group "Manufacturing Control" in this field, we develop and adapt sample preparation methods and analytical methods to offer our internal and external customers new solutions along the entire process chain of silicon and SiC manufacturing lines – for the characterization of wafers (e.g., Si, SiC), manufacturing processes, process media (e.g., ultra-pure water, chemicals), and supporting materials (e.g., glues, filter material) – and the associated supply chains. Our service portfolio ranges from a single analytical service to a fully integrated development project with troubleshooting and several optimization loops.

TECHNOLOGY AND MANUFACTURING

Adaptive Sampling and Contamination Control Methods for Silicon and SiC Manufacturing Lines and their Supply Chains



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Our characterization methods include the analysis of inorganic (mainly metals, acids and bases), particulate contamination and organic contaminants (mainly airborne molecular contamination-AMC / volatile organic compound – VOC). Our analytical toolset consists of triple quadrupole inductively coupled plasma mass spectrometry (ICPMS), high-pressure ion chromatography (IC), airborne particle counter and unpatterned wafer surface inspection system, gas chromatography mass spectrometry (GCMS) with automatic thermo desorption system (ATD), wafer thermo desorption system and micro-chamber/thermal extractor.

4 Open micro-chamber / thermal extractor for material outgassing tests. © Anja Grabinger / Fraunhofer IISB

The availability of the state-of-the-art analytical equipment and sample preparation methods for various substrates and materials within an ultra-clean and particle free environment is essential for high performance ultra-trace analysis. To meet these requirements, our sample preparation and some of the analytical equipment is installed in an ISO class 3 cleanroom. Depending on the sample methods and measurements, very low detection limits (down to sub-ppt level) can be achieved.

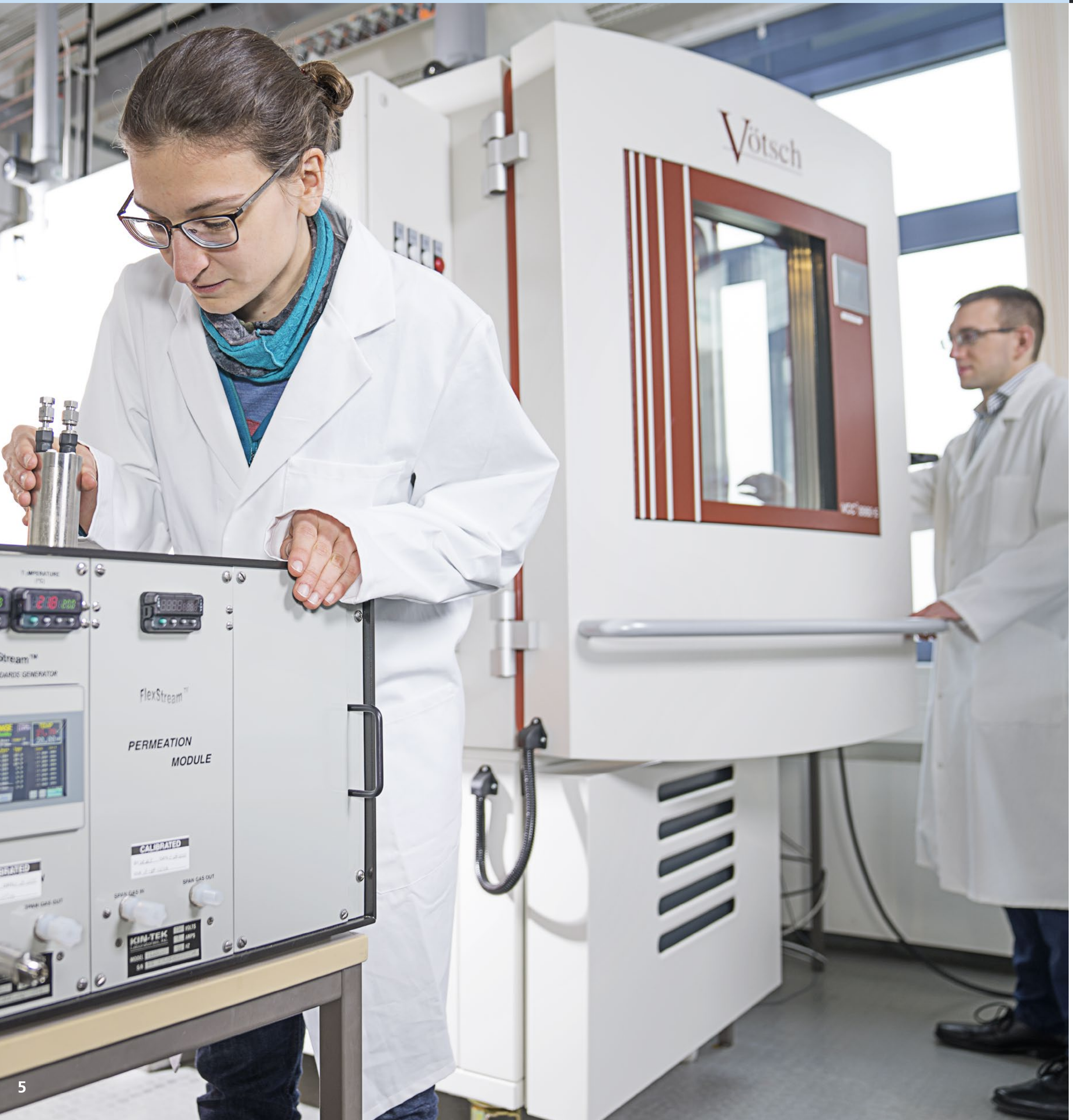
A current example of our adapted sample preparation methods is a vapor phase decomposition droplet scan method using aqua regia to investigate wafer contamination with precious metals (e.g., Pd, Ag, and Au) introduced in power device manufacturing. For investigations of the contamination level in cleanrooms we modified thermal and chemical extraction methods to optimize the analysis of new and used filter material as well as other applications. In particular, the boron release out of particle filter elements were systematically analyzed.

Industrial users of environment control systems generally prefer analytical systems that are automatically operated and can be implemented directly in the manufacturing lines or in the areas to be monitored. For the investigations in cleanrooms and equipment minienvironments classical sampling tubes together with a pump and control unit were integrated into a standardized wafer container, in this particular case a 300 mm FOUP (front opening unified pod), in order to allow to control the ambient of the equipment minienvironment without any manual opening of the equipment.

As another example, there are various systems for air and environmental control available on the market. However, these systems typically use different gas sensors, which have to be evaluated and to some extend calibrated under different conditions. An important aspect here is also the cross sensitivity to different gases. With our experience in gas and environmental control a specific gas sensor testbed was implemented. The gas sensor testbed allows the characterization of all types of gas sensors or gas sensor systems with respect to different target gases (e.g., volatile organic compounds – VOCs). By using a permeation furnace and corresponding permeation tubes, almost any chemical in the relevant concentrations (typical concentration of 10 - 100 ppm) can be provided in the test cabinet at different temperatures (up to 90 °C heat only) and humidity

TECHNOLOGY AND MANUFACTURING

Adaptive Sampling and Contamination Control Methods for Silicon and SiC Manufacturing Lines and their Supply Chains



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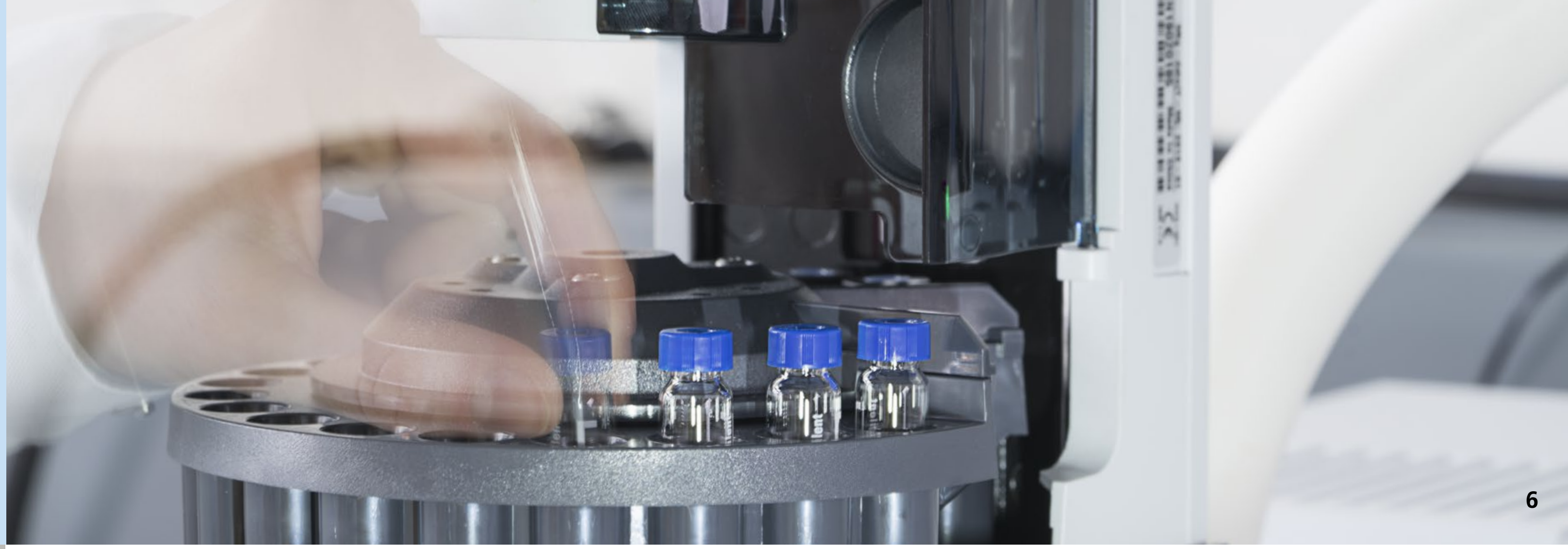
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(10 % - 90 % rH). To calibrate the gas sensor systems and to perform correlation measurements the gas sensor testbed includes the possibility to use classical sampling methods and standard analytical methods in the laboratory (e.g., gas chromatography mass spectrometry or ion chromatography). In addition, test capabilities could be provided for the assessment of sensors or other electronic systems in harmful atmospheres. For this purpose, corrosive gases (H_2S, SO_2, Cl_2 with carrier gas N_2, NO_2 with carrier gas synthetic air) are provided in a corrosion test chamber with a conditioned air volume (10 - 90 % RH, 15 - 60 °C).

5 *Gas sensor testbed at the IISB laboratory.*
© Anja Grabinger / Fraunhofer IISB

6 *Autosampler (close-up) for gas chromatography mass spectrometry analysis of liquid samples.*
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DEVICES AND RELIABILITY

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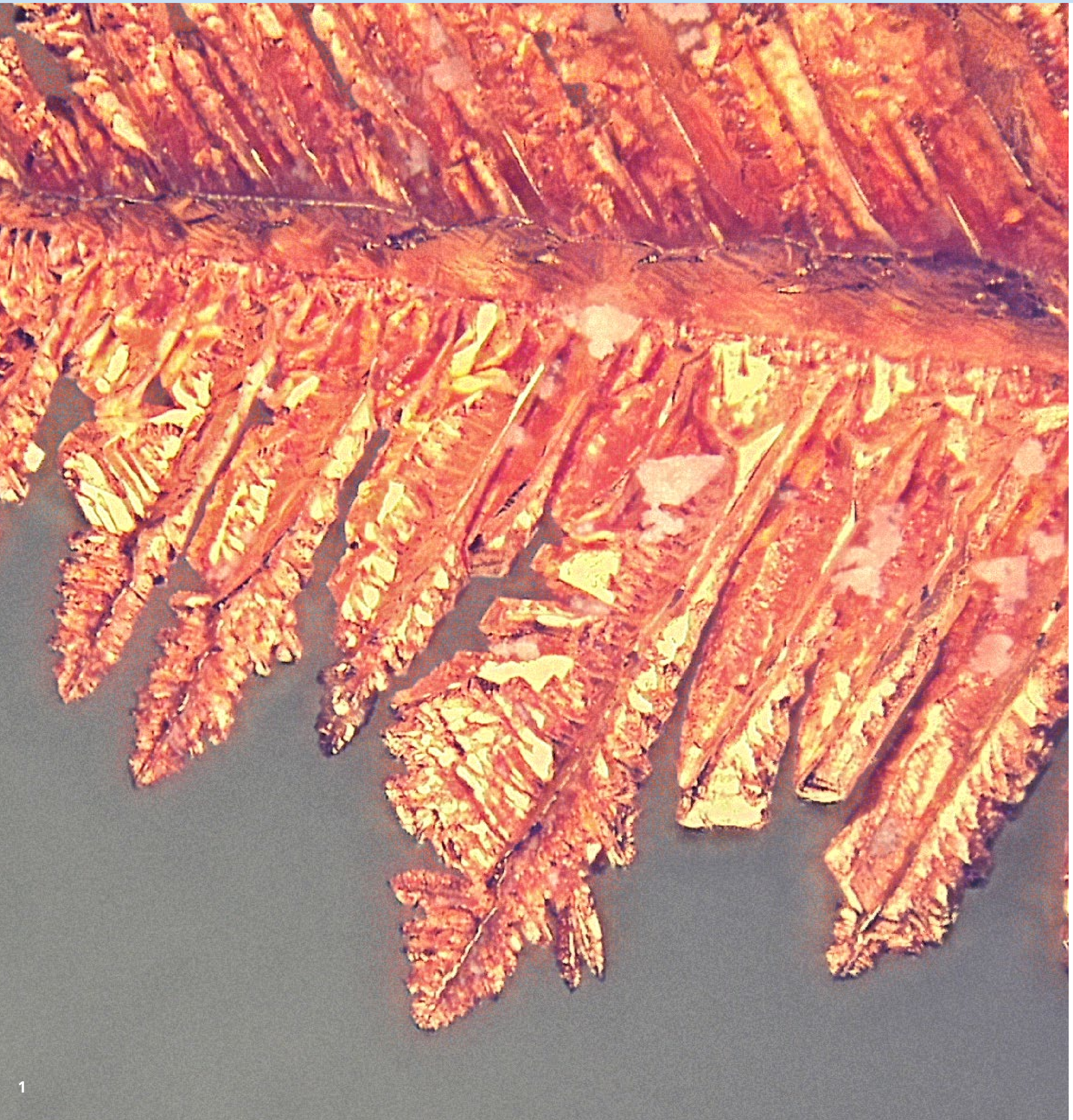

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The department acts as a bridge between the Semiconductor Technology business unit, which is focused on materials and processes, and the application-oriented Power Electronics business unit. The fields of research include design and fabrication aspects of active and passive devices, packaging technology and concepts, as well as electrical characterization, lifetime testing, modelling, and reliability.

On-going development of silicon carbide processing technology for power devices has focused on the implementation of self-aligned process steps in 2019. This technology extends the manufacturing capabilities towards shorter device channels in VDMOS transistors beyond the limitations imposed by photolithography.

In the joint collaboration with the National Institute for Nanomaterials Technology in Pohang, Republic of Korea, Fraunhofer IISB has started implementation of trench etching processes towards a baseline TrenchMOS technology. Results can be expected throughout 2022. The project has moved right into the second two-year stage. Close collaboration between both institutions and significant exchange of staff was continued towards the establishment of subsequent joint R&D activities in Korea and Germany.

The SiC CMOS baseline technology for high-temperature capable circuits was moved forward with the next round of process batches. Presently, the work focuses on process optimization and implementation of analog circuits like high-temperature amplifiers.

Further work towards RC snubbers suitable for switching speed enhancement in SiC-based 1200 V power modules has been carried out to implement the feasibility of technology transfer to an external silicon foundry. Additionally, together with the Leistungszentrum Elektroniksysteme (LZE), efforts are ongoing to identify and address more use cases for this technology.

In the field of packaging, new research projects have been started. MESiC, sponsored in the PREPARE program by Fraunhofer Association, was kicked off in the early year of 2019. PREPARE projects serve the purpose of demanding, cross-institutional preliminary research in preparation for new business fields. These projects intend to lay the foundation for a longer-term alliance between the institutes IISB, IKTS, IMWS, and IWM. Within the MESiC project, a novel thermally extremely stable (up to 400 °C) and highly compact power module concept for SiC devices is being researched and developed. In contrast to previous technologies, the approach is based on the sintering of multilayer ceramic substrates embedding SiC components. The task of MESiC is to achieve the competitiveness of SiC-based electronics in a wide range of power electronic applications like drive inverters. The main goal is to reduce SiC semiconductor costs by a factor of three and at the same time to fully exploit its superior performance characteristics. This project goes hand in hand with the whole packaging strategy followed in this working group.

1 *Copper crystal after corrosion testing.*

2 *Andreas Schletz, head of the Devices and Reliability department.*
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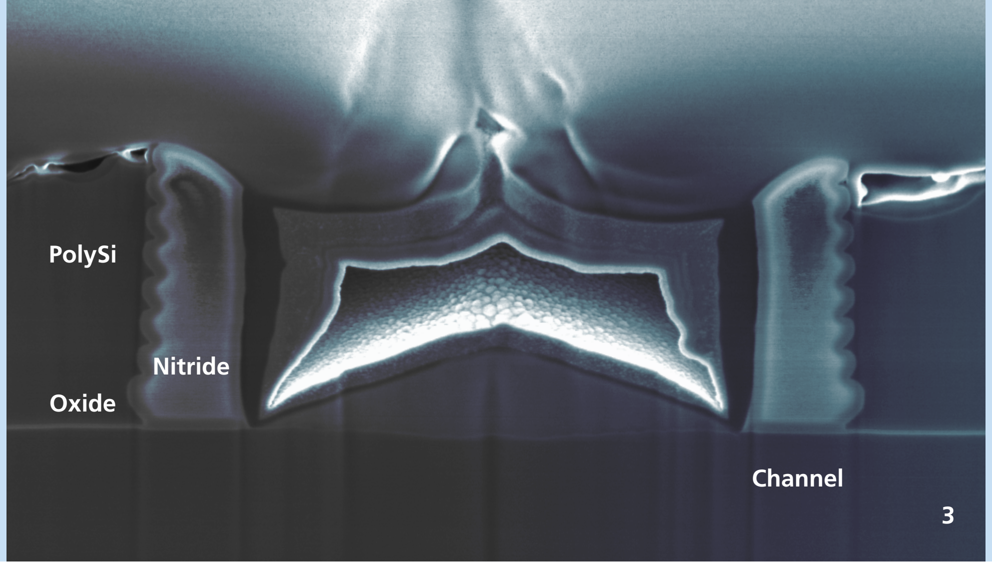
DEVICES AND RELIABILITY

SiC-VDMOS: Beyond the Lithography Limits with Self-Alignment Channels



3 *SEM image of process patterns for self-alignment VDMOS channel structures.*

For the die attach, direct bonding technology was further researched and developed. Now it is possible to stack semiconductor components without any additional intermediate layer like solder or sinter material. Furthermore, not only devices may be attached without an intermediate layer, but also contacting lead-frames or flexible circuit boards can be assembled. Thermomechanical testing is ongoing right now to show the relevance of this technology for power electronics.

More tools have been installed and set up. The complete packaging line from storage, printing, die bonding, soldering and sintering, encapsulation, and testing is available in a high-quality packaging lab.

The research activities concerning testing and reliability have now settled in the new "environmental test lab". Thanks to the FMD project, the new tools are now nearly completely finished. The new possibilities are fitting perfectly to the department's road map enabling the future needs for power electronics. Especially wide band gap devices, such as high voltage, high temperature, and low on-resistance silicon carbide devices can be tested without compromises.

Thanks to the ongoing project "Research Fab Microelectronics Germany (FMD)," sponsored by the Federal Ministry of Education and Research, this new hardware was installed that allows new research to be well equipped for the future.

Material characterization for the next generation of lifetime modelling for power electronics is ongoing. A project started to investigate thick-copper-based insulating substrates. Modelling and the simulation tools were improved. Now, it is possible to simulate power modules with their electro-thermo-mechanical behavior. Therefore, different simulation tools had been linked together to enable the three domains. Within the simulation, thermal heating and cooling is possible like it happens in the real application by passive and active temperature cycles. All material and simulation models are validated by experiments to get a good confidence in the results. The output is a reference value for the lifetime.

Everything is connected to everything. Within the publically funded research project "SiCool", supported by the Federal Ministry of Education and Research, a new genetic optimization algorithm for different target values was developed and tested. First, the thermal resistance of direct cooled pin fin cold plate structures is enhanced automatically. The target is to get an optimized power module setup with a minimized chip size at a required lifetime and lowest cost at the same time. Therefore, the workflow is established.

In addition to the variety of publicly funded projects, there were a huge number of joint industrial projects in all research fields. The topics ranged from assistance and consulting to large feasibility studies and process and technology developments for devices, packaging, and testing. The applied research within the department is financed by an industrial budget contribution of well above 40 %. This perfectly achieves the Fraunhofer target.

Many thanks to all colleagues for their great support during challenging times and the excellent work that has led to success and keeps the institute ready for the future.

SIC-VDMOS: BEYOND THE LITHOGRAPHY LIMITS WITH SELF-ALIGNMENT CHANNELS

Industry drives the commercialization of Silicon Carbide power transistors on 150 mm wafers at full speed towards application in energy-efficient converters. An increasing number of fast-followers are moving into the market. Fraunhofer IISB uses its qualified 150 mm 4H-SiC baseline planar processes to develop and manufacture such kind of devices using an 800 nm UV stepper technology. While this lithography resolution is sufficient for 1200 V VDMOS transistors, the overlay accuracy of the stepper tool limits the electrical performance of such power devices. To further increase integration density, a large density of cells within an integrated circuit is needed to obtain low on-state resistance power devices. Self-aligned processes, e.g., the self-aligned channel for MOSFET, help to downscale the cell pitch and as a result increase the cell integration in the devices.

The self-aligned channel for SiC-based MOSFETs in planar technology implemented by Fraunhofer IISB uses the spacer process, which is also fully compatible with silicon CMOS technology where this process flow is part of the lightly-doped-drain process. In a first step, a thin oxide is deposited onto the front side of the wafer. Subsequently, deposition of a thick polysilicon layer is carried out. This polysilicon layer is subsequently patterned on the front side using photolithography and dry etching in order to create a hard mask for the aluminum ion implantation (so-called PBASE region). Here, the thin oxide acts both as a stopping layer for the etching process and as a scattering oxide for the ion implantation. After the implantation, silicon nitride of a well-defined thickness is deposited onto the wafer. A feature of the conformal LPCVD deposition is to form a layer of a homogenous thickness even on rugged topographies – in this case on the polysilicon mesa, trench bottom, and sidewalls. Next, dry chemical etching is used to etch back the silicon nitride anisotropically. This step removes the silicon nitride from the mesa and trench bottom but leaves it on the trench sidewalls as depicted in the SEM image (Fig. 3). Hereby, a silicon nitride spacer with well defined width is created next to the polysilicon region. The thin oxide again acts as a stopping layer for the etching process and simultaneously as a scattering oxide for the subsequent nitrogen ion implantation (so-called SOURCE region). The channel length of the MOSFET

DEVICES AND RELIABILITY

New Environmental Test Lab at Fraunhofer IISB

is defined between the PBASE edge and SOURCE and it corresponds roughly to the width of the spacer, which in turn equals the thickness of deposited silicon nitride. The main advantages of this process are its self-alignment and achievable short channel lengths, compatibility with the silicon technology and application even for a high-temperature ion implantation.

Hence, it is possible to manufacture 1200 V VDMOS transistors with on-state resistance below 6 mΩcm². This approach is already well known from silicon technology and augments our tool box of fabrication processes for baseline VDMOS transistors. This SiC baseline technology is, to the best of our knowledge, free of third party IP. Thus, collaboration in this field allows our partners to quickly step into the SiC power device domain with a competitive device design and process portfolio that can be tailored to their needs.

NEW ENVIRONMENTAL TEST LAB AT IISB

Corrosion and corrosion protection are studied at Fraunhofer IISB including basic research concerning corrosion mechanisms, environmental testing, and condition monitoring and corrosion protection for power electronic devices.

During the last year, the environmental laboratory was completed by a temperature shock chamber (temperature range: 60 - 300 °C), a corrosive gas test chamber (temperature range: 15 - 85 °C, humidity range: 10 - 90 °C and range of gas concentration: up to 50 ppm for H_2S, SO_2, and NO_2), a HAST (Highly Accelerated Stress Test) system for accelerated testing with high humidity, high temperature, and air pressure, and a salt spray test chamber.

The new equipment was provided by the investment program "Forschungsfabrik Mikroelektronik Deutschland" (FMD) of the "Bundesministerium für Bildung und Forschung" (BMBF).

In the fully equipped environmental laboratory, different application conditions are simulated and environmental influences can be investigated. Customized as well as standardized tests like salt spray test (e.g. DIN EN 60068-2-52), thermal shock test (e.g. DIN EN 60068-2-14), damp heat test (e.g. DIN EN 60068-2-67) and corrosive gas tests (e.g. DIN EN 60068-2-42, DIN EN 60068-2-43 and DIN EN 60068-2-60) can be performed. An overview of all environmental tests being performed at Fraunhofer IISB can be found in the table beside (Fig. 5).

4

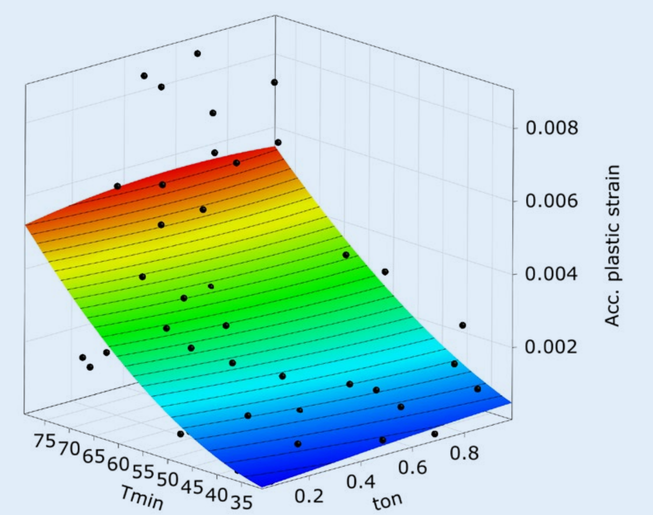
Device	Environmental test	Temperature range in °C	Humidity range in % RH	More parameters
Cyclic corrosion test chamber	Salt spray test	RT+5 to +50	Up to 93	
	Condensation test	RT+5 to +42		
Air-air temperature shock chamber	Temperature Cycling	-70 to +400		
Climatic corrosive gas chamber	Corrosive gas test (single and mixed gas)	+15 to +85	10 to 90	NO_2: up to 50 ppm SO_2: up to 50 ppm H_2S: up to 50 ppm Cl_2: up to 1 ppm
HAST system / pressure cooker	Highly accelerated stress test	+50 to +142.9	75 to 100	Pressure: 0.020 to 0.196 MPa
Environmental stress chamber	High temperature and high humidity test	-75 to +180	10 to 98	

4 *Dendrites between two circuit carrier pads within a condensation test. © Thomas Richter / Fraunhofer IISB*

5 *Table: Overview of testing capability in the fully equipped environmental laboratory at Fraunhofer IISB*

After environmental testing, different methods for damage analysis are available at Fraunhofer IISB. Besides optical techniques like light and scanning electron microscopy, surface analysis techniques like energy dispersive X-ray spectroscopy (EDX), focused ion beam (FIB) cuts, X-ray photoelectron spectroscopy (XPS), and scanning acoustic microscopy are available.

Characterization of coatings for corrosion protection is performed to develop new coatings, compare different coatings and investigate the influence of environmental testing on coating properties. One important parameter is the adhesion of coatings that can be evaluated by different methods (scratch test, pull test, shear test, etc.). Furthermore, laser interferometry is conducted for the analysis of coating thickness and quality. Thermo-gravimetric analysis (TGA) and differential scanning calorimetry (DSC) is available to get information about different properties, like melting point, melting range, heat capacity, etc. Further analyzing tools include Fourier-transform infrared spectroscopy (FTIR), radiography / computer tomography, partial discharge measurement, and comparative tracking index (CTI) is ready to use.



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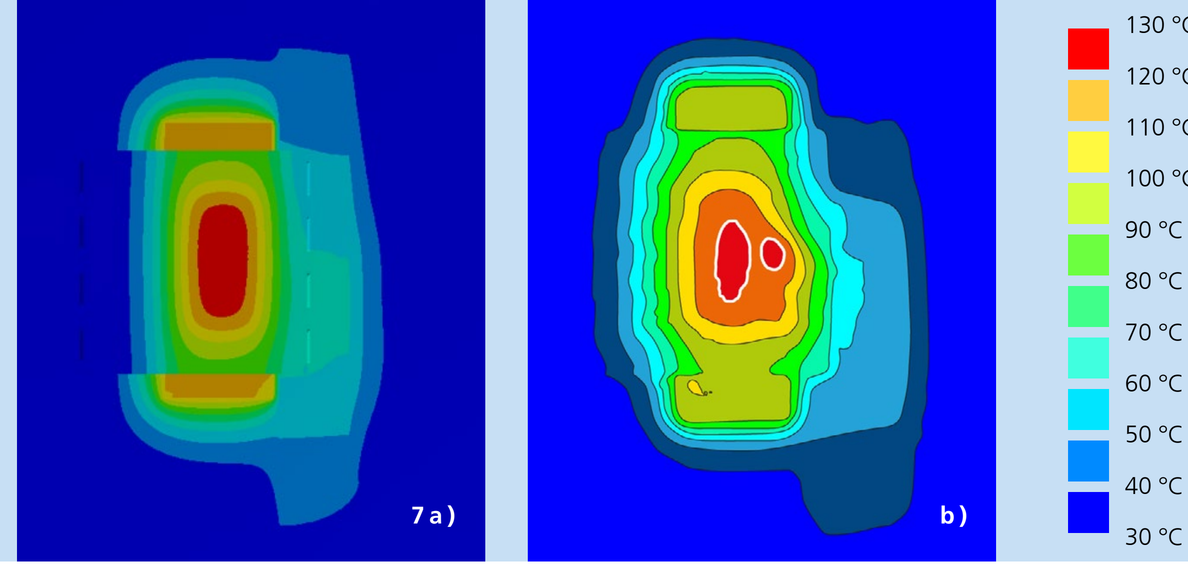


FROM MATERIAL CHARACTERIZATION TO FE-BASED DESIGN OPTIMIZATION

In the field of lifetime and reliability prediction, as well as optimization of power electronics assemblies, numerical simulation is successfully being used. The idea is to support the development engineer in making important decisions during the product design process. Typical situations, where FE simulation is applied, straddle all physical domains, where the spatial field information has to be taken into account. The applications can range from computing the electrical current density distribution and electrical fields over the dissipated heat and temperature field for cooling optimization to mechanical forces and displacements for studying substrate deflections or failure mechanisms occurring in accelerated lifetime tests. In addition, all kinds of couplings between the different physical domains are intensively used. What all of these variants have in common, however, is that they are being used to study the influence either of the spatial geometrical properties or the material behavior on the assembly properties. Some insights regarding the activities in this field of the group "Test and Reliability" can be found in the following subchapters.

Mechanical characterization and modelling of packaging materials by nanoindentation for lifetime prediction supported by FE simulations

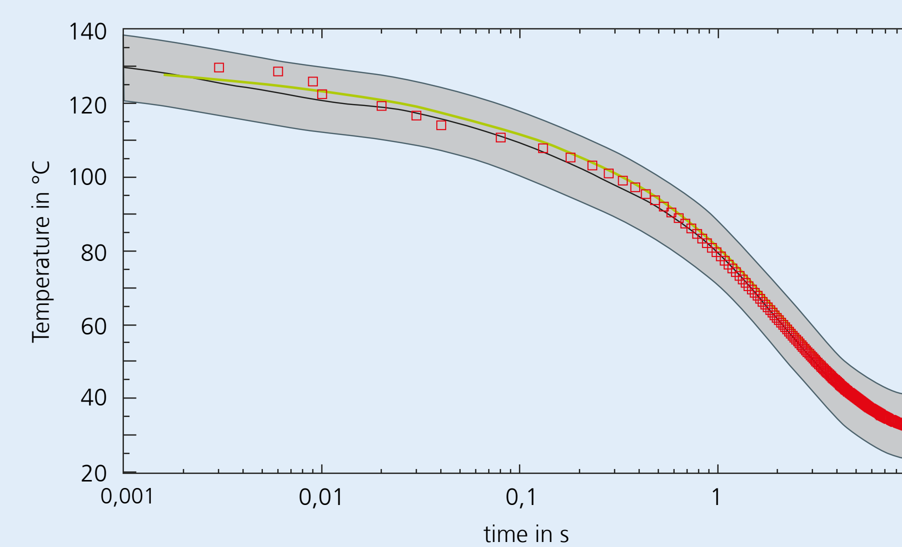
Many properties of the materials that are used in power electronics assemblies show a strong dependency on the individual manufacturing process. If one wants to carry out FEM simulations of an electronics assembly, the material properties need to be determined as accurate as possible including all the processing history, as long as no process simulations are done in advance. When standard tests such as uniaxial tensile, shear, or bending tests, are planned, sample preparation can become a very time intensive and failure prone task. In this case, all interactions from the different manufacturing processes need to be taken into account.

An optimal method of testing in the aforementioned situation is nanoindentation. With the standard cross-sectioning preparation method, samples can be produced relatively simple and fast. The advantage is that the indentations can be made on the cross-section of the samples, where under favorable conditions all relevant materials are present and, most important, have seen exactly the same process history as in the manufacturing routine of the product. However, there are certain steps to be taken in this process. After the mechanical cross sectioning, an ion-polishing step is recommended in order to reduce the hardening depth from the mechanical grinding and polishing on the surface. Also "multi-layering" should be avoided. This means that the layers located under the layer of interest have to either be removed or taken into account in the analysis procedure.

Keeping this in mind, nanoindentation makes it very easy to obtain the elastic modulus, in a temperature range from room temperature up to 500 °C, for the most common electronics packaging materials. Even rate-dependency can be addressed.

When it comes to nonlinear inelastic material properties, additional support by FE analysis is needed, since the complex state of stress does not allow for analytical calculation of the parameters for the nonlinear behavior laws. If the material is assumed to have an isotropic behavior, a 2D finite element model with rotational symmetry is sufficient. This saves computational time and delivers acceptable results in most cases. The aim is to evaluate the computed load-displacement curve from FEA for an initial guess of the material parameters and to compare it with the experimental measured load-displacement curve. By varying the material parameters within a meaningful range, it is possible to investigate the influence of the parameters on the predicted load-displacement curve. The number of parameters as well as their range can then be reduced, in order to obtain the input parameters with a significant influence on the response. With the help of multivariate polynomials or Kriging interpolation, a meta-model can be build, which can be further used for direct optimization with algorithms like "nonlinear programming by quadratic Lagrangian" for finding the material properties, which represent the best matching result between experiment and simulation.

After the development of this procedure, it was possible to parameterize all necessary temperature dependent material behavior laws for different assemblies with GaN power semiconductors



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6 *Dependence of accumulated plastic strain on T_{min} and t_{on} for a power cycling test.*

7 *Validation of the simulated temperature distribution by means of IR thermography:*
a) *Simulated,*
b) *Measured.*

8 *Validation of the simulated average temperature in the semiconductor by using the PCT data and a custom-designed validation setup.*

DEVICES AND RELIABILITY

From Material Characterization to FE-based Design Optimization

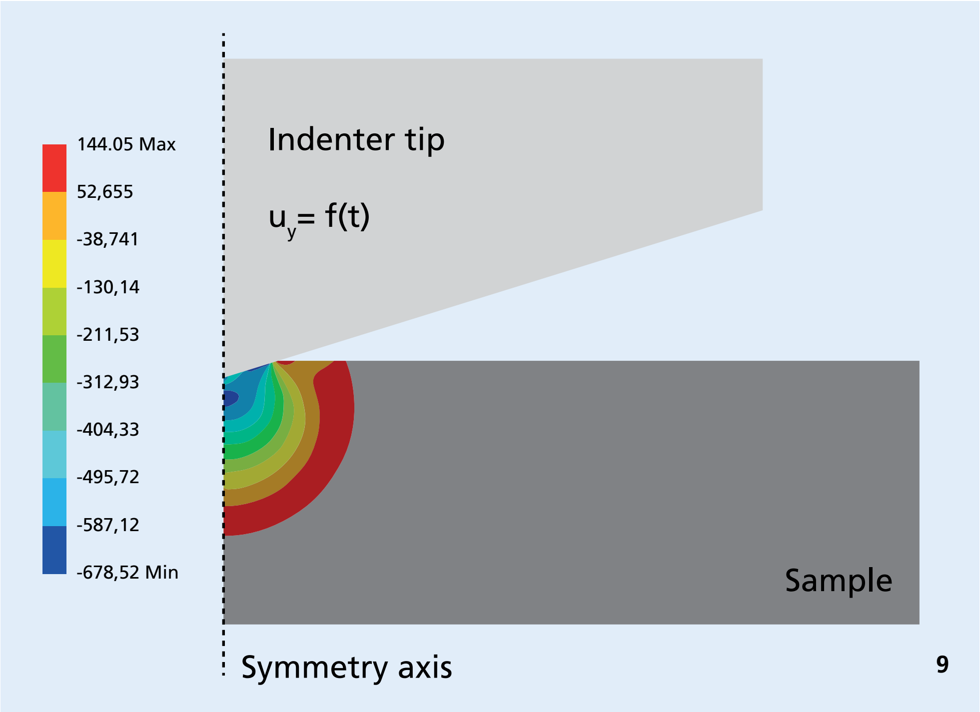
soldered on PCBs. The collected data is currently used in FE-Simulations that contribute to build lifetime models together with power cycling test results.

Finite-element analysis for lifetime testing and design optimization

With lifetime tests often requiring excessive amounts of time and financial resources, numerical analysis has become a very useful tool in complementing as well as partially supplementing experimental activity.

By using numerical methods such as finite element analysis coupled with sensitivity analysis and stochastic optimization techniques, great progress has been made with respect to understanding and predicting the impact of both design (e.g., layer thickness, bondwire diameter, etc.) and test parameters (e.g., pulse length t_{on}, coldplate temperature T_{min}, etc.) on the sample degradation during lifetime tests. This provides valuable information, and example of which can be seen in Fig. 6, which is used to optimize and tailor design lifetime for specific applications.

The complex task of predicting component lifetime and developing reliable lifetime models using test data has been a central topic of our group's activities for many years. Using the physics-of-failure approach in combination with numerical simulation has made it possible to correlate the test results with the numerical results, allowing for a direct way from mission profile to accurate lifetime prediction.



Besides using the current state-of-the-art finite element numerical solvers, development activities in the field of physics solver coupling are also taking place within the group, keeping up with the constant need for more realistic simulation models.

Numerical model validation is a key part of the simulation workflow. Several non-destructive measurement methods such as thermography and digital image correlation have become standard procedure to verify the validity of the generated numerical results. This has enabled an overall improved confidence in the simulation data as well the development of accurate validation strategies.

A successful example of numerical model validation can be seen in Fig. 7 and Fig. 8, where the simulated temperature distribution at the end of the heating cycle of the power cycling test is being compared to the measured one. The procedure was developed and applied within the BMBF funded project HELENE (FKZ.: 16EMO0231). Now it is possible to do efficient lifetime simulation in direct link to the packaging technologies, geometries, materials, and concepts.

9 *2D-FEA model of the nanoindentation process for the inverse material model parameterization.*

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VEHICLE ELECTRONICS

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Challenging applications up to megawatt of electric power

The vehicle electronics department is covering a wide field of power electronic solutions in various applications. The original focus on electric passenger cars is opening up to electrified buses, trucks, and construction vehicles, as well as trains and ships with much higher requirements on power and lifetime. An extremely challenging field is electric air mobility. On one side there is the urban air mobility with different kinds of multi-rotor aircrafts with vertical takeoff and landing (VTOL) capability with a voltage range up to 800 V and requirement of 200 kW up to 1000 kW of electric power, on the other side there are hybrid-electric regional aircrafts with power demands in the megawatt range. But both applications need very lightweight and highly reliable power electronic solutions.

To tackle all these upcoming challenges, the Vehicle Electronics department is working on mechatronic integrated drive inverters, DC/DC converters and chargers with latest silicon carbid (SiC) or gallium nitride (GaN) semiconductors. The mechatronic integration of the drive inverter with the electric motor saves space and weight of an additional housing and the failure prone three-phase AC cables and connectors. Another positive effect of the integration is the significant reduction of the electromagnetic interference (EMI) caused by the power electronics. The EMI of ultra-fast switching of SiC and GaN power electronics is an upcoming challenge, making filters more space consuming. To optimize the EMI spectrum and reduce the size of the filter elements, the Vehicle Electronics department is working on new simulation models and concepts to achieve low EMI emissions by design of the power electronic system, optimized passive and active filters, and software. This opens up the possibility that the electrical engineer can simulate and adapt the electrical design to the EMI specifications during the early stages of the design process.

Beside the challenges, the SiC and GaN power devices enable the realization of much smaller and more efficient DC/DC converters necessary for future powertrains powered by fuel cells for heavy-duty or autonomous vehicles and aircrafts. Placed between the fuel cell and the electric drive and a power in the range up to several hundreds of kilowatt, a high efficiency is mandatory for improved range of the vehicle and low cooling effort on the power electronic converter. To reduce the size of DC/DC converters further, the research project "InKoleZ" is focusing on galvanic isolated resonant DC/DC converters with a switching frequency of 1 MHz and an optimized transformer and EMI filter for a small size 11 kW off-board charger, for an "in-cable charger box".

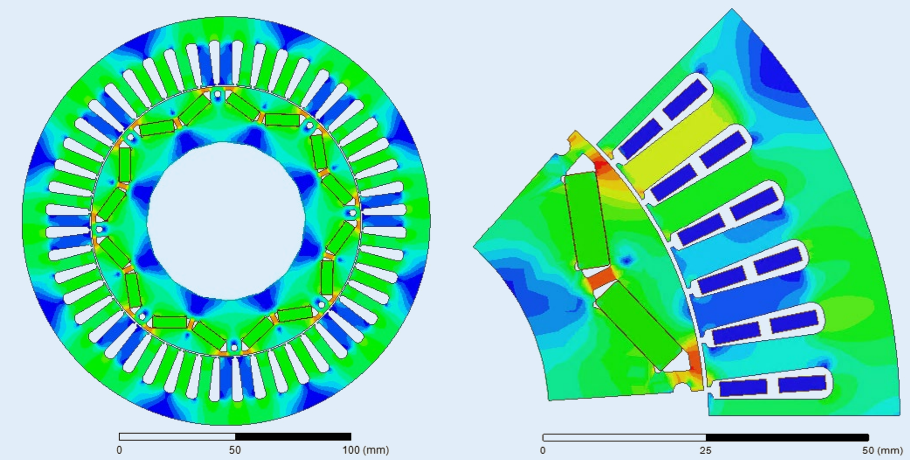
Besides small and efficient solutions, there is a growing demand for reliable power supply for fail operational functionality for upcoming autonomous vehicle and aircraft solutions. Therefore, the research project "HiBoard" is focusing on safe and fail operational power supply concepts for autonomous vehicles. To fulfil the challenging requirements of a fail operational power supply a

1 *Intelligent energy distribution for fail-operational power supply of future autonomous vehicles. © Anja Grabinger / Fraunhofer IISB*

2 *Dr. Bernd Eckardt, head of the Vehicle Electronics department. © Kurt Fuchs / Fraunhofer IISB*

VEHICLE ELECTRONICS

Electric Motor Design



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special power supply unit with a DC/DC converter, safety power switches, and a super cap energy storage is developed.

A great event was the IISB Annual Conference on vehicle electronics combined with DRIVE-E summer school and the "WAVE", an electric vehicle tour with its final destination in Erlangen. This gave the 50 participating students a focused view on the challenges for future electric vehicles and the possibility for testing different kinds of common and brand new electric cars.

With several new topics, many successful projects, and a great team, the Vehicle Electronics department is looking back on an eventful year. Sincere thanks to all my colleagues for the extraordinary work, the support of our public and industrial partners, and Fraunhofer Gesellschaft for great support.

ELECTRIC MOTOR DESIGN

A step forward to complete cognitive drive train development

The Drives and Mechatronics group started motor design activities to establish a much deeper understanding of the interaction between the drive inverter and the motor. This is essential for the cognitive power electronic solutions, with the goal that the drive inverter can monitor and detect upcoming defects in the motor, like isolation problems or a wear out of the ball bearings. To gain knowledge, a complete 150 kW electric motor was developed. During the design process the magnetic and mechanic design was simulated and optimized for high torque and a peak output power of 230 Nm and 150 kW at 800 V supply voltage. The maximum shaft speed is up to 20.000 rpm, and a six phase approach is chosen to get a small and scalable multi-phase drive inverter.

With the simulation model of the motor first evaluations of different failure scenarios were investigated to detect, e.g., a wear out of the bearings. The very positive simulation results were now verified on our motor test bed in order to continue the training of the software algorithm of the cognitive drive inverter.

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3 Highspeed permanent magnet synchronous machine (PSM) ready for assembly. © Anja Grabinger / Fraunhofer IISB

4 Magnetic field simulation with and without torque for the high-speed PSM.

INTELLIGENT ENERGY SYSTEMS

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The department "Intelligent Energy Systems" develops the technologies for the digitalization of the power electronic and energy conversion in the transportation and energy domains. The department integrates these technologies in interconnected intelligent energy systems, building the "Cognitive Power Electronics" ecosystem initiated at the Fraunhofer IISB. Its research and development efforts are focusing on cutting-edge power and control electronic hardware, as well as on advanced software algorithms and data processing technologies making intensive use of artificial intelligence, targeting electrical power conversion and electrical energy storage in mobile and stationary applications, covering the entire power range from a few watts up to several gigawatts.

Organization of department

The department is organized in five working groups with a total of about 35 researchers. A highly skilled staff in mechanics, mechatronics, electronics, embedded software, informatics, and computational mathematics with long-term experience in industrial R&D projects and technology transfer allows us to successfully support and accompany our customers in addressing today's digitalization and tomorrow's digitalization challenges in the energy and power businesses. The close cooperation with the Chair of Power Electronics (LEE) at the University of Erlangen-Nürnberg in Germany provides us with access to the latest fundamental research results and an attractive pool of highly skilled and motivated students.

Activities of the research groups

The group "Data Analytics", headed by Dr. Martin Schellenberger, helps our partners and customers to get the most out of their data in the context of IoT and Industry 4.0. The group takes an application-oriented approach that includes system analysis, conception, data collection, filtering, clustering, and finally the development and implementation of intelligent algorithms in industrial processes or in embedded systems.

The group "Energy Technologies", headed by Dr. Richard Öchsner, investigates and optimizes intelligent and decentralized energy systems like fuel cells and redox-flow batteries for the energy and transportation domains. The focus is on the integration of different physical storage systems (i.e., electrical, thermal, hydrogen), and on the intelligent interconnection as well as control – also based on forecasts – of different energy areas (sector coupling, peak load reduction).

The group "Industrial Power Electronics", headed by Markus Billmann, supports our customers in solving power electronic challenges in the field of multi-level converters of all voltage ranges. Whether development support or problem analysis for running facilities and equipment, the

1 *Test stand for the investigation of hydrogen-based fuel cell systems. © Kurt Fuchs / Fraunhofer IISB*

2 *Dr. Vincent Lorentz, head of the Intelligent Energy Systems department. © Kurt Fuchs / Fraunhofer IISB*

INTELLIGENT ENERGY SYSTEMS

Advanced System Integration of Fuel Cells and Electrolyzers

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list of strengths in the field of troubleshooting of this group is large: longstanding industrial application experience, fast response time, and familiarity with industrial processes.

The “Battery Systems” group, headed by Martin Wenger and Radu Schwarz, is working on innovative solutions for lithium-ion-based electrical energy storage systems for stationary and mobile applications. The activities range from the development of battery management systems (e.g., BMS platform foxBMS), algorithms for battery state estimations and predictions, up to the design of full-custom battery systems for large applications like racing cars, submarine exploration robots, airships, and electric gliders.

The group “DC Grids”, headed by Bernd Wunder, focuses on innovative solutions for local DC grid systems. Their work ranges from applied research, e.g., on safety and stability issues of DC networks, through concept studies, up to the development of innovative grid components, such as customized DC/DC converters, DC plugs, and protection devices. Bernd Wunder also represents the DC topic on boards such as VDE/DKE, IEC, eMerge Alliance, and IEEE Smart Grid.

Sincere thanks to all colleagues in the department for their extraordinary dedication, to all our supporters from industry, politics, and Fraunhofer, and to the entire staff of the IISB.

ADVANCED SYSTEM INTEGRATION OF FUEL CELLS AND ELECTROLYZERS

Hydrogen is expected to play a key role in future energy and transportation systems. In many present applications and future scenarios, energy from the electrical grid is converted into hydrogen via electrolysis. For converting the stored energy within the hydrogen back into electrical energy, fuel cells are a promising and suitable solution for many applications. Fraunhofer IISB uses its competencies to enhance existing hydrogen power technologies and to develop new routes for the system integration of innovative hydrogen storage technologies.

Having lots of expertise in power electronics and different kinds of electrical and thermal energy storage systems, Fraunhofer IISB takes a holistic look at the whole power systems, in which electrolyzers and fuel cells are integrated. For example, within commercially available mobile applications like the hydrogen car Toyota Mirai or the hydrogen train Alstom iLint, hybrid systems combining fuel cell stacks and battery systems are implemented to cover the load requirements. Due to the limited dynamics of several hydrogen technologies, the hybridization with fast-acting battery storages is necessary to fulfil highly dynamic load requirements. Furthermore, a smart

3 *Innovative energy storage system using a PEM fuel cell, an electrolyser, and a special reactor for processing a liquid organic hydrogen carrier. The modular and scalable energy storage system is integrated into the DC microgrid of the Fraunhofer IISB.*
© Kurt Fuchs / Fraunhofer IISB

4 *DC infrastructure room at Fraunhofer IISB including the central distribution cabinet with the main protection devices, an intelligent DC grid controller, several lithium-ion battery systems, and the AC grid coupling unit.*
© Kurt Fuchs / Fraunhofer IISB

INTELLIGENT ENERGY SYSTEMS

Advanced System Integration of Fuel Cells and Electrolyzers
Smart DC Microgrids For Increased Energy Efficiency

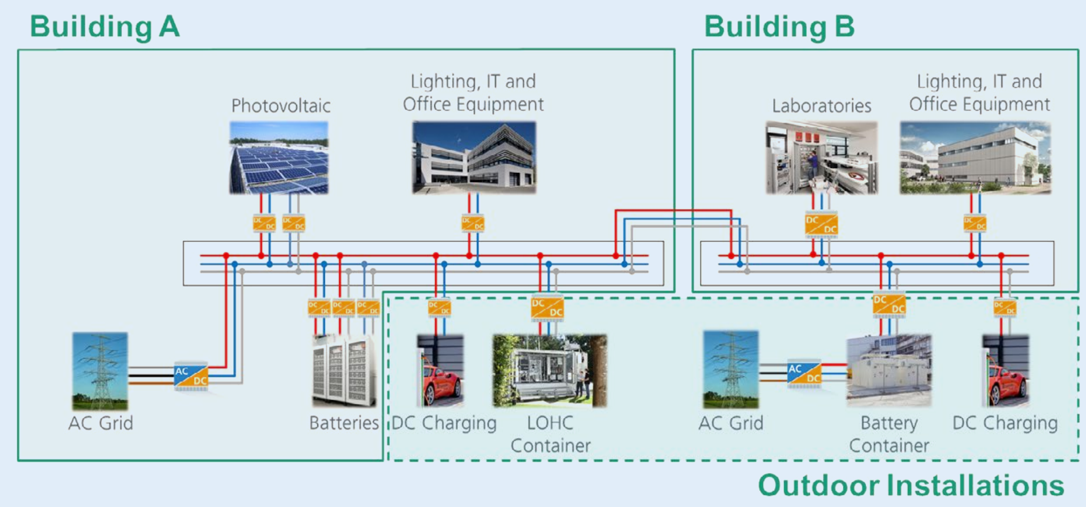
hybrid system design and operation offers to enhance lifetime of components and to optimize parameters like weight, efficiency or costs. Therefore, the overall system design including power electronics architecture as well as control strategy development and implementation are main elements of the advanced system integration realized at Fraunhofer IISB.

Looking at the unique research platform for power systems based on the storage of hydrogen within liquid organic hydrogen carriers (LOHC) at Fraunhofer IISB, the so-called LOHC container, hybridization plays a major role, too. This research platform includes the electrolyzer to convert electrical energy into hydrogen, which is stored compact and safe under ambient conditions for pressure and temperature within a liquid carrier, and the fuel cell to convert the stored hydrogen into electrical energy.

The electrolyzer and the fuel cell are based on the PEM (polymer electrolyte membrane) technology and are integrated in the DC microgrid of the Fraunhofer IISB via self-developed power electronics. The hybrid operation of electrolyzer or fuel cell and the hydrogen storage unit requires the researchers at Fraunhofer IISB to develop specific control strategies regarding operational constraints, e.g., the different dynamic behavior of the single components. In addition to the LOHC container, a flagship project of LOHC technology realized together with the University of Erlangen-Nürnberg, the scientists at Fraunhofer IISB gathered extensive knowledge on the operation of PEM fuel cells with a high content of non-hydrogen gas in a specially developed hydrogen test bench in recent years. With the developed system setup, PEM fuel cell systems became able to run with nitrogen contents of up to 60 %. It was also demonstrated that PEM fuel cells can be operated with exhaust gas of the epitaxial process used in the semiconductor manufacturing. The described test bench is also used to investigate hybrid systems of fuel cell and battery.

However, hybrid system solutions also require a hybridization of competencies. Besides the extensive operating experience with hydrogen systems, relevant core competencies at Fraunhofer IISB are battery technology, power electronics, and development of control strategies and optimization algorithms. In addition to various cooperations with industrial partners in the field of hydrogen technology, the institute expands its existing competencies in the field of the novel LOHC technology by a close cooperation with the leading experts of the Helmholtz Institute Erlangen-Nürnberg (HI ERN).

The acquired competencies and existing cooperation enable the scientists at Fraunhofer IISB to create tailored simulation models for various application scenarios. For example, a simulation model of a fuel cell-battery hybrid system with hydrogen storage in LOHCs for the mobile application in trains is used to develop control strategies and to find an appropriate dimensioning of fuel cell, battery, and LOHC unit to cover the dynamic load requirement.



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4 *Real DC microgrid demonstration plattform at Fraunhofer IISB.*

As a research service, Fraunhofer IISB offers the simulation-based design and control strategy development of hydrogen based power systems for defined stationary and mobile applications. The new hydrogen laboratory in the extension building opened in 2019 also offers additional possibilities for the setup and investigation of further research demonstrators. The scientists at Fraunhofer IISB are pleased to pave the way for hydrogen technology to a broader future application through advanced system integration within current and future projects.

SMART DC MICROGRIDS FOR INCREASED ENERGY EFFICIENCY

DC microgrids have established themselves well over the last couple of years as a beneficial approach to interconnect distributed renewable energy resources, battery storage systems, and loads locally. After maturing in telecommunication and data center applications, DC microgrids are now sparking interest also for industrial applications comprising a large number of speed-regulated drives. The fundamental challenges within these applications are power quality issues due to harmonic distortion caused by a large number of passive rectifiers on the one hand and the difficulty to regenerate braking energy on an economical scale on the other hand. DC microgrids offer a cost-efficient solution for these challenges by eliminating the rectifier stages through provision of a common DC bus supplying the drive inverters directly. In addition to that, controlling the power flow within a DC microgrid is significantly easier in comparison with the AC mains, because the number of state variables directing the power flow is reduced from the quantity of two in the AC case, namely line voltage level and frequency, to only one in the DC case, which is the bus voltage level. Fraunhofer IISB has participated in different projects involving DC microgrids for industrial applications targeting different power levels

Large-scale industrial production fed by DC power

The project "DC-Industrie", which was funded by the German Federal Ministry of Economic Affairs and Energy (BMWi), aimed at showing the benefits of local DC microgrids for different branches of industry like car manufacturing, machine tool building and plant engineering. After defining a broad consensus among different industrial equipment manufacturers on a comprehensive operating concept for the grid, three demonstration sites were built, commissioned, and scientifically analyzed. Fraunhofer IISB contributed in three fields: investigation of a decentralized load flow management concept that only requires the grid-side voltage value to determine the infeed level of a power source, advanced methods to measure the grid impedance within noisy industrial environments in real-time, and development of high-efficiency DC-to-DC converter

INTELLIGENT ENERGY SYSTEMS

Smart DC Microgrids For Increased Energy Efficiency

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systems. The converters were deployed to interconnect a battery storage unit and a wood-working tool machine. Besides providing resiliency, the deployment of the active controlled storage system contributed to improve the total energy efficiency of the machine by up to 10 % by regenerative braking energy that would otherwise be dissipated into heat.

DC microgrids for rural areas

The rapid and progressive connection of distributed renewable energy resources, mainly PV generation, to low-voltage distribution grids especially in the rural areas of Germany over the last two decades has led to several issues among which significant deviations of AC line frequency from the nominal value and overload of distribution lines and cables being the most critical ones. Fraunhofer IISB addresses these challenges again by promoting DC microgrids that are adapted to the specific needs of the typical consumers found in these respective areas: small and medium-sized businesses, agriculture, and private households. The DC-Grid Manager concept provides an integrated solution for these challenges by provision of up to eight power DC-to-DC converter channels within one housing. The system is ideally suited for setting up a local energy system containing PV generation, battery strorage units, and loads. This system approach enables enhanced local utilization of PV generation and helps to relieve the public AC grid.

Blockchains as an enabling factor for new business opportunities

Besides developing highly efficient and versatile power electronic converter systems, Fraunhofer IISB is also conducting investigations on new concepts related to and making use of data security, data integrity, and trusted electronics. Blockchain-based trading systems for local energy markets are also investigated. This further helps to increase the utilization of local energy resources with the additional benefit on creating financial revenues especially for less favored regions.

Smart safety devices for modern DC microgrids

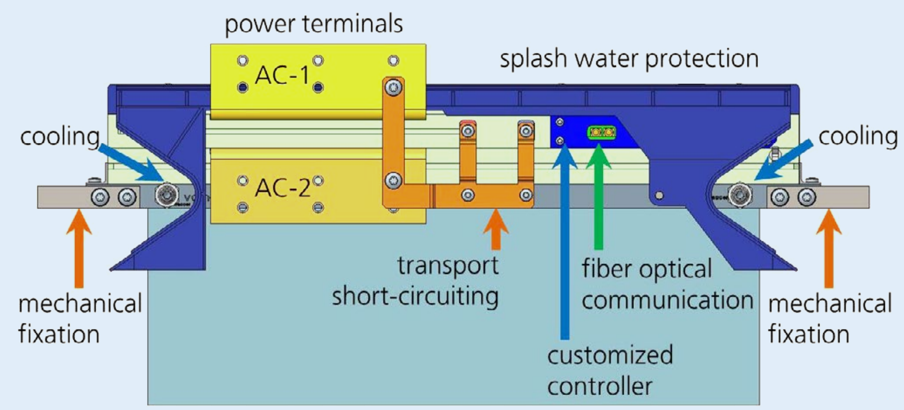
Operating a modern and DC microgrid requires not only converters, storage systems and renewable energy sources, but also an efficient and safe infrastructure to transport the energy. Since DC installations pose several challenges that usually do not occur in normal AC installations – e.g., long standing switching arcs or a change of direction in power flow – those must be addressed as well. Hence, in the research project „DC-Schutzorgane“ („DC safety elements“), funded by the German Federal Ministry of Economic Affairs and Energy, a comprehensive protection system for DC microgrids was developed. Besides responding to the specific technical requirements of DC technology, the system and the individual protection devices – e.g., against arc faults and overvoltages – provide additional information about grid status and their own state of health, allowing predictive maintenance as well.

5 *Main test enviroment from the ETIBLOGG project to evaluate a blockchain market for small-size decentral energy actors.*
© Bernd Wunder / Fraunhofer IISB

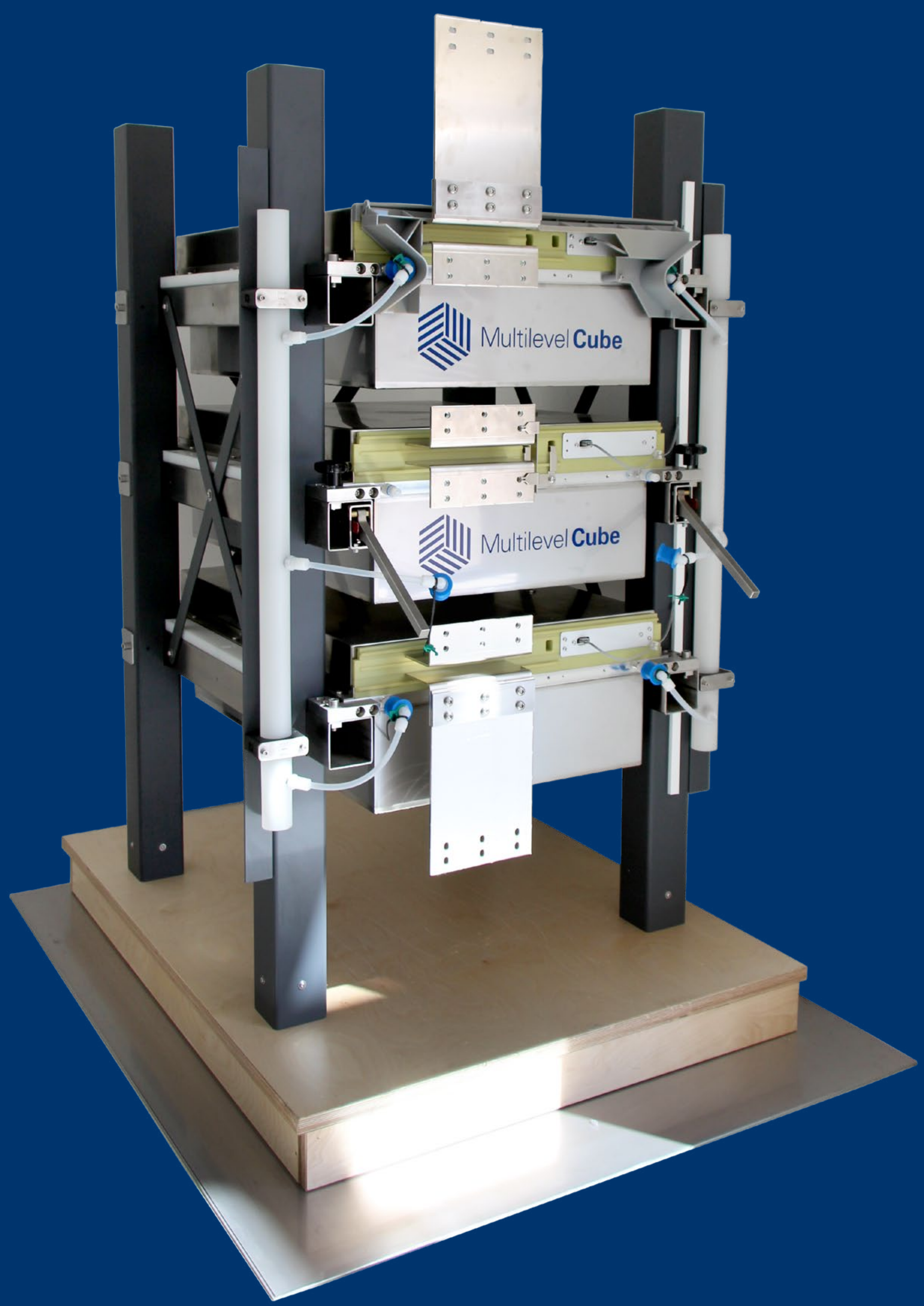
6 *A battery system for peak load reduction is part of the DC Grid.*
© Kurt Fuchs / Fraunhofer IISB

INTELLIGENT ENERGY SYSTEMS

Energy Management – Standardization in Multi-Level-Converter Submodules



Same mechanical family outline – various topologies & voltages 8



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ENERGY MANAGEMENT – STANDARDIZATION IN MULTI-LEVEL-CONVERTER SUBMODULES

The world's growing demand for electrical energy needs a new concept to ensure a reliable and also flexible power scaling. Today systems from HVDC to STATCOM are provided by a few big players worldwide. For scalable high power applications up to the gigawatt-range they all use the principle of modular multi-level converters (MMC). Such systems are based on submodules, mostly voltage source half- or full-bridge topologies. From up to several tens to thousands of such »megawatt-submodules« are arranged side by side in converter halls, similar to bricks in a wall. The basic functionality is always the same: the design varies in small details depending on the provider.

Standardization in modular multi level submodules – A new standard for high energy transportation and power quality systems was introduced by Fraunhofer IISB

Comparing existing designs we identified that they all appear very similar, but not adapted for a future up-scaling. Enhancing power will lead to more and more »hard-to-handle« mechanical concepts while their aspect ratio will run into an undesirable direction. Spare part exchange time – a major system cost aspect – will increase as a consequence.

A similar design pattern within such players is obvious; but all observed modules seem to be »developed for a current demand«, not really considering future needs and requirements. This means various MMC generations appear quite similar at first glance, but have never been harmonized in terms of interface or rack-mounting compatibility. This leads to a variety in non-compatible mechanical outlines. If we additionally consider reduced product life cycles in high-voltage IGBTs, which follow the 600 V to 1700 V IGBT chip and packaging technology mainstream, this principle will lead to an immense amount of variants.

Long term compatibility and availiability

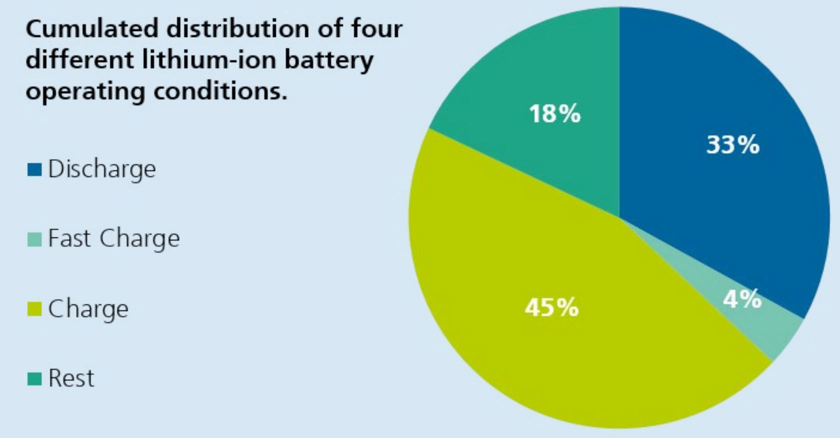
By requirements, each version has to provide spare parts for several decades, which is a real challenge because downward compatibility was never a design issue from the start. At the Fraunhofer IISB, a new approach was developed in cooperation with an independent industrial stakeholder. The plan is to provide such submodule family members for the global market with centralized perfective maintenance, quality and quality management, thus establishing a downward-compatible MMC submodule standard.

7 *Very simple rack mounting and minimized service time.*

8 *Standardized interface, arranged along one side of the submodule, power scaling by Z-, or Y-axis.*

INTELLIGENT ENERGY SYSTEMS

Energy Management – Standardization in Multi-Level-Converter Submodules
foxBMS – Free and Open BMS Platform Focused on Functional Safety and AI



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Design expertise

The Fraunhofer IISB has a long-term successful expertise in the field of MMC submodule design. Based on a family platform idea this approach provides identical interfaces and same rack design for various IGBT voltages and topologies. A much better form factor will guarantee not only a volume neutral power enhancement for future generations, but also a nearly ideal mounting space for power electronics components and a seamless integration. The design also introduces water cooling for key components.

Design verification

Meanwhile, explosion sustainability tests have successfully been performed at the Fraunhofer IISB. Such validation is mandatory for MMC systems, because chain reactions from level to level must be excluded. Even at highest DC-link voltage level the mechanical design provides enough strength to keep all debris and plasma inside the submodule level. No impact to neighbours has been validated.

FOXBMS - FREE AND OPEN BMS PLATFORM FOCUSED ON FUNCTIONAL SAFETY AND AI

The last years have shown a strong market demand for battery systems with higher energy densities, longer lifetimes, and lower costs, but without compromising safety. To provide developers, engineers, and researchers worldwide a high flexibility Fraunhofer IISB has established the free and open Battery Management System platform "foxBMS" (foxbms.org). This BMS platform consists of a modular hardware and software architecture and a complete toolchain for software development. With regard to the implemented functional safety features, as well as the accurate and stable battery state estimation, the second generation of foxBMS provides a BMS platform beyond state-of-the-art.

Functional safety

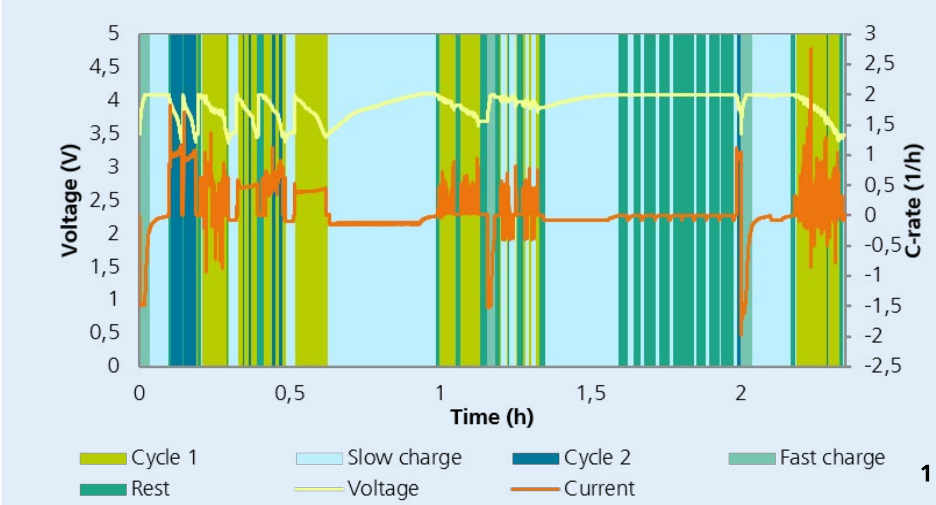
The second generation of foxBMS was designed to be conformal with functional safety requirements for various domains (e.g., automotive, aviation, railway, industrial, marine). Therefore, key components of the hardware architecture have been selected to not only cover the ISO 26262, but also the IEC 61508 and other domain specific standards. As a key component, the Texas Instruments TMS570LC4357 was selected as the MCU, paired with two NXP FS8530 system basis chips. This enables the designer to reach high safety integrity levels or even directly use pre-certified parts for its design.

AI workflow for precise state estimation in embedded systems

An artifical intelligence (AI) based algorithm was implemented on foxBMS in order to improve battery state parameter analysis and estimation. For this purpose, a large amount of data was generated by our own fleet of electric vehicles, and preprocessed, so that an appropriate training of the neural network (NN) is guaranteed. The data is the result of the measurements done by the foxBMS platform, consisting of a foxBMS Master Unit and one Slave Unit per battery module. Both are integrated into commercially available electric vehicles and approved to be roadworthy by TÜV. The measured data from foxBMS and current sensor along with others such as vehicle speed, acceleration, and vehicle position are transmitted over CAN to a data logger integrated into the vehicle. This data is regularly uploaded to a server and shared with a High Performance Cluster (HPC).

9 Clustering of a dynamic load profile of a lithium-ion battery into relevant battery operating condtions.

10 Cumulated distribution of four different lithium-ion battery operating conditions.



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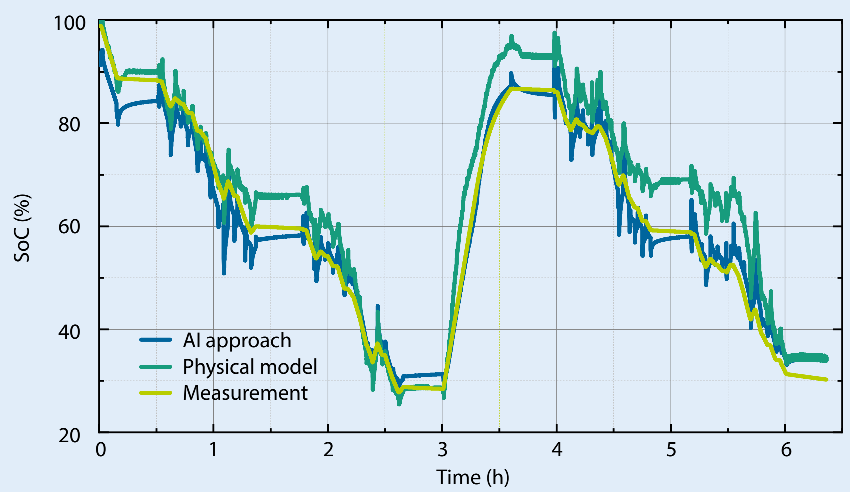
With this setup, real-world driving data has been accumulated for more than a year. During this period, more than one terabyte of driving data has been logged. For a better understanding of the data, clustering algorithms are used, which divide the driving profiles into clusters. Based on the clustering, the most relevant information is extracted, which is used for an optimized training of the NN. As a result, the NN achieves a better generalizability, whereby a precise SOC estimation is ensured even for dynamically changing environment and working conditions. The

INTELLIGENT ENERGY SYSTEMS

foxBMS – Free and Open BMS Platform Focused on Functional Safety and AI Data Analytics

input data is used to train a long short-term memory (LSTM) NN offline on a HPC to predict the SOC of the battery with the precise Coulomb Counting as learning reference. After a hyperparameter optimization, the generated NN is compiled for the embedded device and flashed on the BMS. By using highly adaptable and real-time capable data-driven approaches, foxBMS is able to accurately model the highly non-linear behavior of LIB caused by changes of environment and working conditions all along the battery lifetime.



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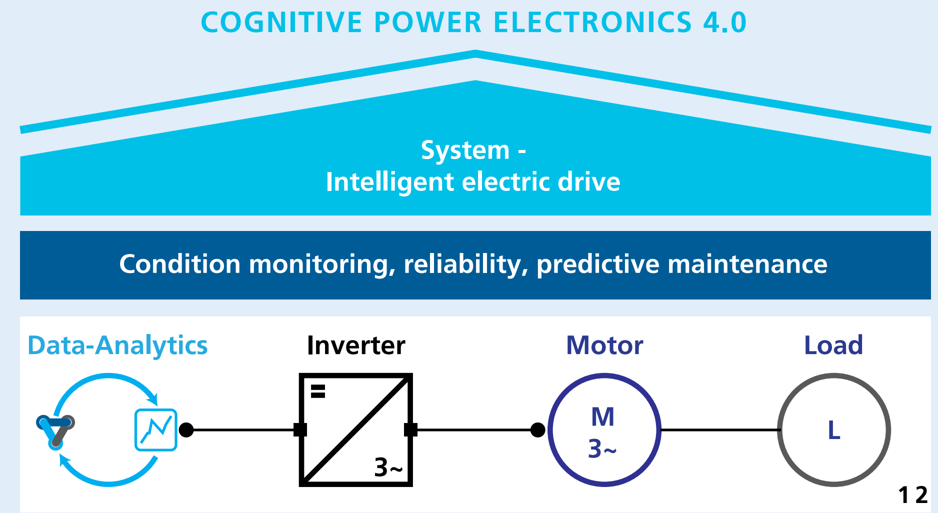
DATA ANALYTICS

We support our partners to get the best out of their data in the context of IOT and Industry 4.0. We follow an application-oriented approach that includes system analysis, design, data acquisition and finally the development and implementation of intelligent algorithms on the edge or in the cloud. In doing so, we pursue two main areas of work: Cognitive Power Electronics 4.0 and Dr. Production®.

Cognitive power electronics 4.0

Power electronic converters form the basis of modern electrical and electronic devices in households, industrial plants, and in mobility. They convert electrical energy, switch loads, regulate electrical drives, and much more. For this purpose, they continuously record parameters such as current, voltage, and their change over time. Therefore, the circuits in themselves bear the potential to directly determine the state of the connected overall system, e.g., the energy network, a production plant, a storage system, or an electric motor, and to make intelligent decisions.



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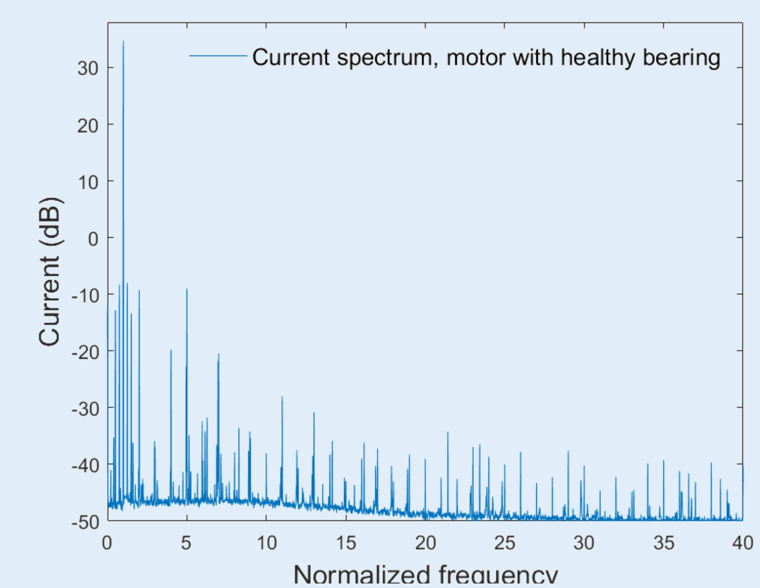
At Fraunhofer IISB, we established the new research field „Cognitive Power Electronics 4.0" to develop power electronic converters that can be used as intelligent modules and are able to make intelligent decisions regarding the connected system – not least in the context of Industry 4.0.

Example: Intelligent drive technology

Within the project Leistungszentrum Elektroniksysteme (LZE) Phase II - Intelligent drive technology, we develop and investigate new Permanent Magnet Synchronous Motors (PMSM) and inverter with integrated data analytics capabilities at the edge to improve detection of anomalies and prediction of potential motor faults. Data analytics is conducted using the electrical parameters available from the inverter (Fig. 13).

Within the first project year, work focused on the development of the PMSM motor and the development of AI-based algorithms to detect characteristic spectral features from the motor current signals, which indicate healthy and faulty motors states with high resolution, and signal-to-noise ratio. Additionally, the spectral analysis is applicable for a consistent investigation of different motor speeds. The applicability of the spectral analysis for detection of irregular motor states by machine learning was investigated on a reference data set.



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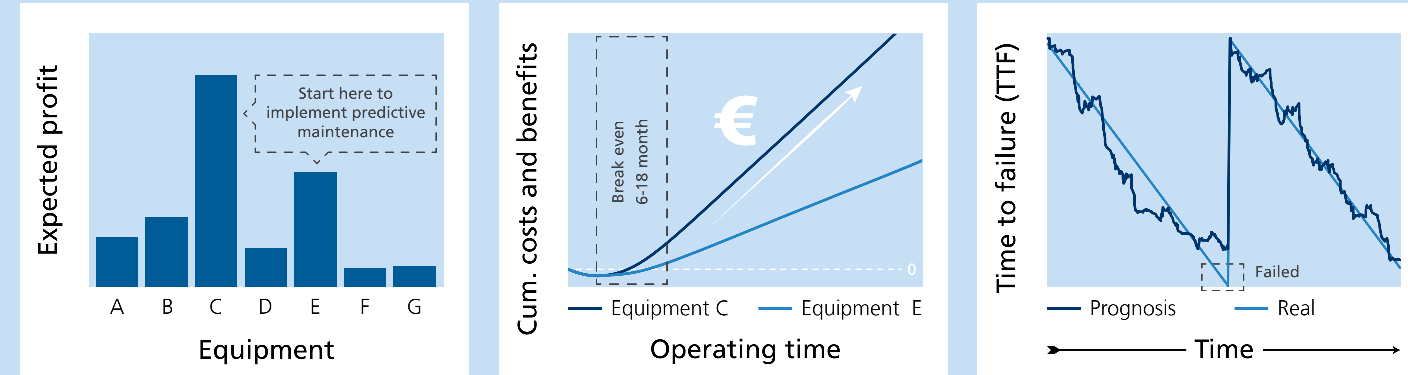
11 *SOC prediction using physical and AI-based models for a dynamic loading profile with Coulomb Counting (CC) as reference.*

12 *CPE 4.0 for condition monitoring and predictive maintenance of drive systems. Data analytics for fault detection and prediction is conducted on available electrical signals from the frequency converter.*

13 *Motor current frequency analysis for detection of healthy and fault states: Current spectra can be resolved with high resolution, excellent signal-to-noise ratio and can be applied for a consistent analysis at different motor speeds.*

INTELLIGENT ENERGY SYSTEMS

Data Analytics



Individual consulting and conception **Analysis of production process and data collection** **Development and implentation of intelligent algorithms** 14

Fig. 14 shows a characteristic current spectrum of a healthy motor with a very good spectral resolution and signal to noise ratio. In the ongoing second year of the project, we focus on the demonstration of the analysis methods at the example of artificially induced bearing faults and the transfer of the methods to other motor systems.

Dr. Production®

Dr. Production® is our application-oriented and customer-focused service for data-driven production and process optimization. This service paves the way for the integration of beneficial ideas from the context of Industry 4.0 into existing manufacturing environments (for details see: www.dr-production.de). With Dr. Production®, we provide holistic solutions in three interrelated modules following the specific objectives (Fig. 15): First consulting and conception, second production process analysis and data collection, third algorithm development and test implementation. Depending on the given task, this chain of modules is run through completely or in parts.

In order to achieve custom-tailored solutions, our methodologies include proven, but appropriately adapted approaches of project planning and implementation. Moreover, Fraunhofer IISB's wealth of experience in applied machine learning and artificial intelligence (AI) is used here, which covers a pool of verified procedures and algorithms. Latest research and development activities complement the existing elements both on conceptual and technological level.

Examples: "Smart Experiments" and cyber-physical systems for semiconductor manufacturing

In 2019 we continued the development of a concept for "smart experiments" within the European project iDev40 (Integrated Development 4.0), now entering concept validation in Fraunhofer IISB's π-Fab, which offers prototyping services for electron devices. In brief, the "smart experiments" concept considers the whole life cycle of information in a fab with the aim of achieving an accelerated transfer from process development up to ISO-certified production.

Beyond that, we developed together with our partners AI-based solutions to optimize everyday production. One of them is dedicated to the recognition of mechanical misadjustments of production equipment in semiconductor manufacturing: Since 2017 we investigate the backend process chain »die attach – optical inspection – wire-bonding – molding« in the Bavarian-funded project CPS4AuP (Cyber-Physical Systems for Assembly and Packaging). At the core of the project, we developed an algorithm for failure state recognition on the wire-bonding tool, based on available production data. In a prototypic implementation, we achieved detection accuracies for failure states above 90 percent. Together with our partners, we now implemented a first version of an IT-architecture for transferring the results to the production line.

Collaboration in data analytics and AI

Both areas, Cognitive Power Electronics 4.0 and Dr. Production®, rely on state-of-the-art know-how in data analytics and the application of AI and machine learning algorithms. Since these fields of expertise are developing at a dramatic pace, strategic collaboration is essential to develop innovative solutions based on state-of-the-art models and algorithms. In-house, we benefit from the close cooperation with the department "Modeling and Artificial Intelligence" (MKI) and its group "AI-augmented simulation". Beyond that, IISB is a founding member of the ADA LOVELACE-CENTER, the newly established competence center for industry-oriented data analytics and AI, located in Nuremberg.

14 *Dr. Production® consists of three focused modules: Conception, data collection and analysis, and development and implementation of intelligent algorithms.*

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EVENTS

More Space for Energy Research

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MORE SPACE FOR ENERGY RESEARCH

1 *The new extension building B of Fraunhofer IISB in Erlangen, exterior view from the east, with battery containers in the foreground.*
© Kurt Fuchs / Fraunhofer IISB

2nd extension building of Fraunhofer IISB inaugurated in Erlangen

On July 8th, 2019, the extension building of the Fraunhofer IISB in Erlangen was officially inaugurated. The new laboratory facilities serve the development of state-of-the-art power electronic systems for electrical energy supply and electromobility as well as the research and testing of complex energy infrastructures on an industrial scale.

After a construction period of about three years, the extension of the Fraunhofer IISB in Erlangen was officially celebrated. In addition to the Bavarian Minister of Economic Affairs and Deputy Prime Minister Hubert Aiwanger, Erlangen's First Mayor Dr. Florian Janik, the President of the University of Erlangen-Nürnberg Prof. Joachim Hornegger, and Fraunhofer Executive Board member Andreas Meuer expressed their best wishes for the IISB in their welcoming speeches. Various laboratory tours for the guests as well as the symposium "Rethinking Energy Systems" afterwards demonstrated the broad competencies and activities of the IISB in this field.

"A successful energy system transformation does not comprise the sum of individual isolated solutions. It needs an overall concept that combines power generation from renewable energies with storage, mobility, and efficiency strategies. Fraunhofer IISB has understood this – not only for research, but also for the construction of the new building section. At the same time, we recognized that modern equipment is necessary for the development of new technologies. That's why we have provided 7.5 million euros for the extension. It is now possible to continue working at full speed on the energy systems of tomorrow in Erlangen", commented Bavaria's Minister of Economic Affairs, Hubert Aiwanger.

The responsible use of energy is a key element of the Fraunhofer IISB program, both in its facilities and in its research topics. "We are pleased that politicians recognized the importance of this topic at an early stage and are also taking account of this with comprehensive strategic investments in future-oriented energy research in Germany. Fraunhofer IISB would like to thank the Bavarian State Ministry of Economic Affairs, Regional Development and Energy and the Federal Ministry of Education and Research (BMBF) for their support, which has financed the extension with a total of approximately 15 million euros," said Prof. März.

A living laboratory for energy research

Together with extensive outdoor areas, almost 3,000 m² of floor space was created for offices and laboratory facilities that address the actual requirements for the energy supply of the future,

EVENTS

More Space for Energy Research

especially in the industrial sector. In the last ten years, the number of employees has more than doubled and an expansion of the institute became necessary again. The acting director of the IISB, Prof. Dr. Martin März, presented three of the research fields that have been the key to this outstanding success story: Cutting-edge research in the fields of power semiconductor technology, in particular in wide-bandgap semiconductors such as silicon carbide and gallium nitride, power electronics for electromobility, and intelligent energy systems.

In addition to offices and laboratories, the new research complex offers an infrastructure that enables highly flexible integration of a wide range of energy sources using state-of-the-art storage technologies. The focus is on intelligent energy and peak load management. Renewable energy sources, electrical and chemical storage facilities, and loads are efficiently interconnected via a powerful direct current (DC) microgrid. A combined heat and power unit, cold and heat storages, and the growing fleet of electric vehicles at the institute are also integrated. Many talk about sector coupling, but at Fraunhofer IISB it's a reality.

A highlight in the extension building is the large medium-voltage test bed, which allows the examination of test objects with a power of up to 20 MVA and a voltage of up to 30 kV. Using a specially developed modular multi-level converter, it is also possible to simulate network anomalies and failure conditions at a predefined time.

Today, Fraunhofer IISB acts as a real-world energy laboratory for the investigation of energy related questions, open to partners from industry and research. Despite this flexibility, numerous precautions have been taken to guarantee the operational reliability of the institute's extensive high-tech process facilities. The energy requirements of the high-tech infrastructure at Fraunhofer IISB are comparable to those of a small industrial plant. Large amounts of energy are required for the generation of cold and heat, compressed air, vacuum, and ultrapure water, but also for the production of semiconductor crystals, and very high peak loads occur during operation. Today, this complex infrastructure forms a "living" demonstration and test platform for new energy technologies and concepts. Several hundred measurement parameters are continuously recorded and feed a powerful database. Comprehensive energy monitoring, the incorporation of weather data, and highly developed software algorithms using artificial intelligence allow to operate the entire infrastructure in an optimal manner. By optimizing the cooling technology itself, the institute's electricity consumption has been reduced by 20 %. The acquired knowledge, the system technology, and the optimisation algorithms can be transferred to any other energy infrastructure in the fields of industry, commerce, and residential areas.

Fraunhofer IISB: A "living laboratory" and open for partners, whether as a source of real data or for testing own components, system solutions, or algorithms.

2 *The acting director of Fraunhofer IISB Prof. Martin März and the Bavarian Minister of Economic Affairs and Deputy Prime Minister Hubert Aiwanger (right) discuss the potential of innovative energy storage systems based on hydrogen for the Energiewende.*
© Kurt Fuchs / Fraunhofer IISB

3 *Bavaria's Minister of Economic Affairs and Deputy Prime Minister Hubert Aiwanger at the opening ceremony of Extension Building B of Fraunhofer IISB in the new medium-voltage test hall on July 8th, 2019 in Erlangen.*
© Kurt Fuchs / Fraunhofer IISB

EVENTS

DRIVE-E Academy and Study Awards 2019

DRIVE-E ACADEMY AND STUDY AWARDS 2019

Ideas for the future of electric driving

For the tenth time, the DRIVE-E programme for young talents provided students with insights into the variety of electric mobility. Four young high potentials were honoured with the DRIVE-E study awards in Nuremberg in 2019. In 2019 it is clear: The future belongs to alternative drive technologies. The issue of the mobility turnaround is gaining momentum not only in the public debate. Many fascinating new ideas for the future of mobility are also emerging in science: In Nuremberg, four young scientists were awarded with one of the DRIVE-E study prices by the Federal Ministry of Education and Research (BMBF) and the Fraunhofer-Gesellschaft for their innovative work in the field of electromobility.

"In order to address challenges such as global warming, we must also break new ground in mobility. Electromobility offers one way of doing this. It contributes to climate protection. It is all the more important for researchers to gain new insights here. And new knowledge is a key to progress", wrote Federal Research Minister Anja Karliczek in her message of greeting to the young researchers.

The formal award ceremony takes place every year as the highlight of the DRIVE-E Academy. The Academy offers 50 selected participants from all over Germany the opportunity to immerse themselves in the theory and practice of electromobility, related technologies, and concepts for a whole week with lectures, workshops and excursions.

A lot of exciting activities for the anniversary

DRIVE-E was established in 2009 as a joint initiative of the Federal Ministry of Education and Research (BMBF) and the Fraunhofer-Gesellschaft. Since its inception ten years ago, more than 500 young talents, who are enthusiastic about the future of electromobility, have participated in the young academics program. On its tenth anniversary, the DRIVE-E young researchers program once again took place at the Fraunhofer IISB in Erlangen. The DRIVE-E university partner in 2019 was the Friedrich-Alexander University Erlangen-Nürnberg (FAU). The academy program gave the participants the opportunity to get a glimpse of practical experience during excursions to the companies ABL SURSUM, Metz Mecatech, and Continental. At a driving event, the attendees were also able to experience the driving feeling in various electric vehicles themselves. In addition, the students also had the opportunity to participate in the Fraunhofer IISB annual conference on power electronics for electromobility.

4 *Driving event with electric vehicles as part of the DRIVE-E Academy 2019 at Fraunhofer IISB in Erlangen ©: Kurt Fuchs / Fraunhofer IISB*

5 *Award-winners, academy participants, and guests at the presentation of the DRIVE-E Study Awards 2019 at the Museum Industriekultur in Nuremberg ©: Kurt Fuchs / Fraunhofer IISB*

EVENTS

WAVE Trophy Germany 2019

WAVE TROPHY GERMANY 2019

Finish of the e-mobile rally in Erlangen

The world's largest rolling electric car event toured Germany in autumn 2019, and on Saturday, September 21st, 2019, WAVE Germany crossed the finish line in Erlangen. On the Schlossplatz in Erlangen, all interested people could watch the arrival of the electric vehicles and talk to the participants of the rally.

The WAVE Trophy is the world's largest rolling electric vehicle event. Electric car fans have been invited to take part in the WAVE (World Advanced Vehicle Expedition) every year since 2011. With the motto "Sunshine Tour", around 50 different electric vehicles and their teams started at WAVE Germany 2019. They travelled together from September 13th to 21st on a total distance of 1600 kilometres across the west and south of Germany. The big finish with subsequent award ceremony took place on the Schlossplatz in Erlangen. All interested people were invited to see the arrival of the vehicles and to talk to the participants and organizers of the rally afterwards.

Partners for the official conclusion of the WAVE in Erlangen were the City of Erlangen, the Stadtwerke Erlangen, Schaeffler AG, FAU Erlangen-Nürnberg, and the Fraunhofer IISB. Erlangen's First Mayor Dr. Florian Janik, the technical director of the Erlanger Stadtwerke Frank Oneseit, and University President Prof. Joachim Hornegger welcomed the WAVE teams and the audience.

With the WAVE, organisers, participants, and partners want to set an example for a new, environment-friendly mobility and demonstrate its suitability for everyday use. On its way through Germany, the rally passed through some 25 cities and visited numerous companies and institutions that are committed to electric mobility.

The origins of the WAVE Trophy

The initiator and organizer of WAVE, the Swiss Louis Palmer, completed the first round-the-world trip in a solar-powered vehicle in 2007/08, which took him over 54,000 kilometres across 38 countries in just over 18 months. The first electric car race around the world in 80 days followed in 2010. For his commitment to sustainable technology, Louis Palmer was awarded the title of Champion of the Earth by the United Nations Environment Programme. Since 2011, he has been organizing WAVE, which has already toured Switzerland, Austria, Germany, Italy, France, Belgium, the Netherlands, the Czech Republic, and even India.

6 *Finish of the WAVE Trophy Germany 2019 on September 21st, 2019 at the Schlossplatz in Erlangen © Kurt Fuchs / Fraunhofer IISB*

7 *After one week and a distance of 1600 kilometres, 50 different vehicles and their teams arrived in Erlangen. © Kurt Fuchs / Fraunhofer IISB*

EVENTS

The Long Night of the Sciences 2019

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THE LONG NIGHT OF THE SCIENCES 2019

A wide range of insights into IISB's research activities

On October 19th, 2019, the IISB took part again in the biennial "Long Night of the Sciences - Nuremberg, Fürth, Erlangen", where it presented itself to the general public. More than 2000 guests were attracted by an extended offer to visit the IISB personally. Along the unique value chain "From Materials to Power Electronic Systems", the institute's staff offered a wide range of insights into their research activities in the fields of materials research, semiconductor process technology, novel devices and packaging technologies, as well as electromobility, and electrical energy technology.

Crowd-pleasers at the main location of the institute in Erlangen were again the visits to the test centre for electric vehicles, the "Electrotainment" lecture on mega-volts and kilo-amperes, and the guided tours to the hydrogen-based energy storage container.

A completely new presentation in the program was "Pretzfeld – the cradle of modern semiconductor electronics". In a medieval castle in Pretzfeld in Franconian Switzerland, a series of technical and scientific ground-breaking works in the field of silicon electronics were carried out from 1946 onwards. Prof. Georg Müller vividly illuminated this chapter of the history of technology, which is barely known today.

Rare insights into a high-tech laboratory were also given by the popular guided tours through the large clean room laboratory of the University of Erlangen-Nuremberg in cooperation with the Chair of Electron Devices (LEB). The large crystal exhibition fascinated the visitors, as well as the real-time monitoring of energy flows at the institute. A grid demonstrator set up especially for the "Long Night" clearly showed the processes in a direct current grid, and a real wire bonder could even be used to bond chips. In live experiments, printed electronic sensors were shown, which might soon be used in sportswear or in agriculture. How future nano-electronics is being created on the computer today was shown by simulation experts. Furthermore, applications with artificial intelligence were demonstrated. The IISB researchers also explained the extreme demands on the reliability of electronics for energy supply and electromobility and how electric drives will revolutionize not only road traffic but also aviation. The students from the "TechFak EcoCar" team presented their new flying robot and the Leistungszentrum Elektroniksysteme (LZE) also introduced itself.

8 *At the Long Night of the Sciences, visitors of Fraunhofer IISB were able to bond a chip live at the wire bonder.*
© Anja Grabinger / Fraunhofer IISB

9 *One of the highlights during the Long Night of the Sciences at Fraunhofer IISB: Various experiments with large currents and high voltages were presented in the humorous experimental lecture "Electrotainment at IISB".*
© Kurt Fuchs / Fraunhofer IISB

EVENTS

Made in Franconian Switzerland

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MADE IN FRANCONIAN SWITZERLAND

Colloquium on power electronics enlightened the history of semiconductor technology

All that computer technology comes from Silicon Valley? Not at all! What only few people know is that in an old castle in the idyllic village of Pretzfeld in Franconian Switzerland, important groundwork was done in the post-war period. And long before Intel and Co. inventions of worldwide significance were made.

In doing so, technological history was written by pioneering achievements in semiconductor research:

After World War II, the Siemens company was looking for new locations to replace the destroyed laboratories in Berlin. As early as 1944, the well-known physicist Walter Schottky and his family moved from Berlin to Pretzfeld, one of the reasons for the opening of the Siemens laboratory in Pretzfeld Castle in 1946 under the management of Eberhard Spenke. It was a lucky coincidence that with Schottky and Spenke – complemented by Heinrich Welker in Erlangen – several physicists of international standing came together in the region.

Thanks to them, German semiconductor research attained international recognition in the 1950s. The decade from 1946 to 1956 was marked by an extremely dynamic progress. Important developments from Pretzfeld during this period included the process for obtaining ultra-pure silicon, which is now used worldwide and is known as the Siemens process, and the manufacturing of the first silicon power rectifier.

At the beginning of the 1950s, various materials were also investigated for their potential for use in semiconductor devices, including the well-known germanium. However, germanium was not suitable for higher temperatures. Siemens-Pretzfeld relied on silicon – absolutely right – which then began its triumphal march worldwide.

Until the 1980s, researchers in Pretzfeld worked on developments for power electronics. In 1990, the Siemens laboratory was merged with the semiconductor activities of AEG under the name eupec. The location was closed down in 2002.

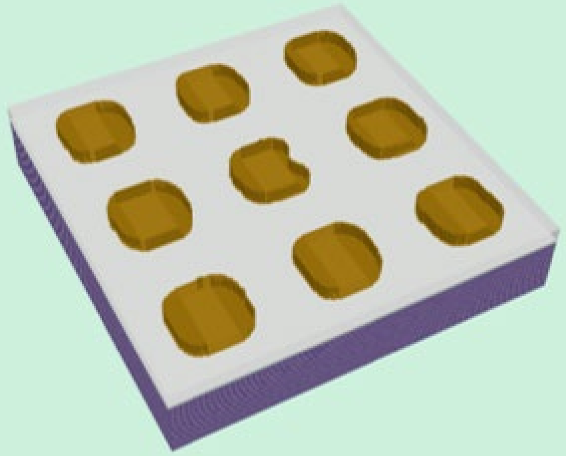
Today, only the Walter-Schottky-Strasse in Pretzfeld reminds us of the high-tech history of the medieval castle first mentioned in 1145. The technologies established in Pretzfeld are now found in every smartphone, laptop, or television, as well as in every solar system, and modern power grids. The Energiewende would not be possible without these fundamentals.

10 *The cradle of silicon electronics: Pretzfeld Castle in the village of the same name in Wiesenttal in Franconian Switzerland.*
© Karlheinz Loch / private

11 *Old production hall in the garden of the Pretzfeld Castle.*
© Karlheinz Loch / private

EVENTS

Made in Franconian Switzerland
17th Fraunhofer IISB Lithography Simulation Workshop



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This almost forgotten chapter in the history of technology was presented on April 29th during the public power electronics colloquium at Fraunhofer IISB. The colloquium is an event in partnership with Fraunhofer IISB, the Bavarian Cluster for Power Electronics, and the Leistungszentrum Elektroniksysteme (LZE).

Prof. Georg Müller, the long-time director of the renowned crystal growing laboratory at the University of Erlangen-Nuremberg, and former Pretzfeld employee Alfred Porst highlighted the history of the Pretzfeld semiconductor laboratory, the technological advances in semiconductor materials and power electronics, and the special working atmosphere at Pretzfeld Castle, which was characterized by collegiality and a spirit of optimism. Numerous contemporary witnesses, former employees, and cooperation partners of the Pretzfeld Laboratory did not miss the opportunity to come to the event and reminisce about the old days.

17TH FRAUNHOFER IISB LITHOGRAPHY SIMULATION WORKSHOP

From September 26th to 28th, 2019, the 17th Fraunhofer IISB Lithography Simulation Workshop was held in Behringersmühle near Ebermannstadt, Germany. As in previous years, renowned scientists from America, Asia, and Europe could be won over as lecturers. The approximately 40 workshop participants from leading industrial companies and research institutions unanimously praised the wide spectrum of topics and the high scientific level of the workshop.

The focus of this year's workshop was on computational methods for EUV lithography (a next-generation lithography technology using a range of extreme ultraviolet wavelengths) as well as on computational metrology in the context of lithography. Particular attention was paid to the use of artificial intelligence (AI). The opening lecture of the workshop dealt with machine learning techniques applied to the fabrication of lithography photomasks.

The numerous multidisciplinary technical discussions were loosened up by a cave tour as well as by a hike followed by a barbecue in a grotto.

Further information on the Fraunhofer IISB lithography simulation workshops is available at:
https://websites.fraunhofer.de/Fraunhofer_IISB_Lithography_Workshop/

12 *Semiconductor production in the historical Pretzfeld Castle: Welding of a quartz glass tube for diffusion experiments.*
© Karlheinz Loch / private

13 *3D lithography mask, which was generated from an SEM image by the IISB simulator Dr.LiTHO. The defect at the structure in the center is classified using artificial intelligence (AI) methods.*

EVENTS

Nationwide School Competition

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NATIONWIDE SCHOOL COMPETITION

3500 pupils from 250 schools from all over Germany took part in the nationwide school competition "Who grows the most beautiful crystal?"

The contest was organized by Fraunhofer IISB, the German Society for Crystal Growth and Crystal Growing (DGKK), and the Leistungszentrum Elektroniksysteme (LZE), together with the P-Seminar "Crystal Competition" of the Eckental High School. Bayern Innovativ with its new materials and energy technology clusters and the companies (alphabetically) Aixtron, AMS, Freiberger Compound Materials, PVA CGS, and Siltronic supported the project financially.

An expert jury selected the most beautiful winner crystals from 350 alum crystals sent in. These crystals are characterized by a double pyramidal shape, are mostly water clear, and as large as possible. The first prize went to the Theodor-Fliedner-Gymnasium in Düsseldorf. Second place was shared by the Max-Planck-Gymnasium in Munich, the Georg-Kerschensteiner-Schule in Müllheim, and the Staatliche Realschule in Dornburg-Camburg. Third place was taken by the Kaufmännische Schulen Hausach. In addition, the Kant-Gymnasium in Boppard and the Staatliche Realschule in Herzogenaurach received special prizes.

All winners will receive a "silicon crystal" with the name of their school as a representative certificate, a monetary award, and a bonus for travel expenses to attend the official award ceremony. The award ceremony will take place on March 12th, 2020 during the German Crystal Growing Conference in Munich.

There was consistently positive feedback for the initiative from the participating schools. Based on this positive feedback, a re-run of the competition is already planned for the 2021/2022 school year. Here are some selected comments:

- "At first, we could not believe that such small fragments can grow into such large, beautiful crystals. You need a lot of patience [...] Even the blackout of the fridge during the summer holidays [...] could not slow us down."
- "The students had a lot of fun and they tried very hard, even though a lot of patience was demanded of them", according to the feedback from the supervising teachers.
- "I think it's great that such a competition gives young people the opportunity to look beyond the classroom and try out scientific work for themselves. Excitingly enough, the format of external competition is often more attractive than the offer of elective lessons at one's own school."

14 *Prize-winning alum crystals in the 2019 nationwide school competition "Who grows the most beautiful crystal? © Anja Grabinger / Fraunhofer IISB*

15 *Winning crystals of the Theodor-Fliedner-Gymnasium Düsseldorf in the nationwide school competition 2019 "Who grows the most beautiful crystal? © Anja Grabinger / Fraunhofer IISB*

EVENTS

Fraunhofer IISB Receives "FamilienLogo"
IISB Research and Development Awards 2019

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FRAUNHOFER IISB RECEIVES "FAMILIENLOGO"

Reconciling work and private life

The IISB is one of 16 Fraunhofer Institutes that have been awarded with the Fraunhofer Family Logo ("FamilienLogo") for outstanding conditions for the compatibility of work and private life.

Fraunhofer is excellently positioned in terms of work-life balance. This is shown not only by the results of Fraunhofer employee surveys, but also by external rankings. To make the successes measurable and visible, and to establish a Fraunhofer-wide standard, the Executive Board of the Fraunhofer-Gesellschaft has decided to give Fraunhofer Institutes with excellent work-life balance capabilities their own seal of quality – the Fraunhofer FamilienLogo. The Fraunhofer FamilienLogo is based on comparable external certifications such as the Work and Family Audit. It covers six different topics, ranging from flexible work opportunities, childcare services, support during parental leave, up to the use of Fraunhofer support services, which are of central importance for the realization of the compatibility of work and family.

The Fraunhofer FamilienLogo was granted to 16 institutes for the next two years, among them the IISB. These institutes are offering their employees excellent family and life phase oriented working conditions.

IISB RESEARCH AND DEVELOPMENT AWARDS 2019

Outstanding achievements in R&D honored

On December 18th, 2019, the research and development awards of the IISB were presented at the annual closing ceremony. These awards, which are presented annually by the Institute's Board of Directors, are given in recognition of colleagues who made outstanding achievements in the areas of research and development.

The 2019 prize winners for the single prize were:

- Sven Besendörfer, for the correlation of growth induced defects with electrical behaviour of GaN power transistors, and, for the team prize,
- Dr. Hubert Rauh and Fabian Streit, for the development of power electronics and controls for the realization of an "electric transmission" in electric motors.

16 *The winners of the IISB Research and Development Awards 2019 (from left to right): Fabian Streit and Dr. Hubert Rauh from the Vehicle Electronics department and Sven Bösendörfer from the Materials department. © Anja Grabinger / Fraunhofer IISB*

17 *The new FamilienLogo of the Fraunhofer-Gesellschaft is an award for Fraunhofer Institutes that offer excellent conditions for reconciling work and private life. © Fraunhofer*

EVENTS

EnCN Energy Award 2019
Best Paper Award for Academic Performance

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ENCN ENERGY AWARD 2019

Simon Quergfelder, member of the Medium Voltage Electronics group in the Vehicle Electronics department at Fraunhofer IISB, has been awarded the EnCN Energy Prize at the annual conference of the Energie Campus Nürnberg (EnCN) for his master thesis "Initial Operation of a 3-Level Inverter to Investigate Different Control Methods and their Influence on Power Quality and Voltage Symmetry". The EnCN Energy Award aims to reward and promote outstanding achievements of young graduates in the field of research and development of renewable energies.

In his work, Simon Quergfelder examined how different control methods for electric motors affect the voltage and current forms at the output of the inverter. He not only showed these relationships theoretically, but also realized a prototype inverter including complex data acquisition. The topic is relevant for the energy-efficient operation and control of electric motors in the automotive, railway, aviation, and power generation industries.

BEST PAPER AWARD FOR ACADEMIC PERFORMANCE

Benjamin Ruccius, member of the Medium Voltage Electronics group of the Vehicle Electronics department at Fraunhofer IISB, was awarded the Best Paper Award – 3rd Prize – at the 10th International Conference on Power Electronics ICPE 2019-ECCE Asia in Busan / South Korea.

In his paper, Benjamin Ruccius presented an approach to estimate the submodule capacitor voltages in a Modular Multilevel Converter (MMC) and to realize this in a hardware test setup. One disadvantage of the MMC topology is the high communication and measurement effort. As the submodule voltages are being estimated, the measurement effort as well as the communication effort between the submodules and the main controller hardware is significantly reduced. Thereby, the reliability of the system also increases.

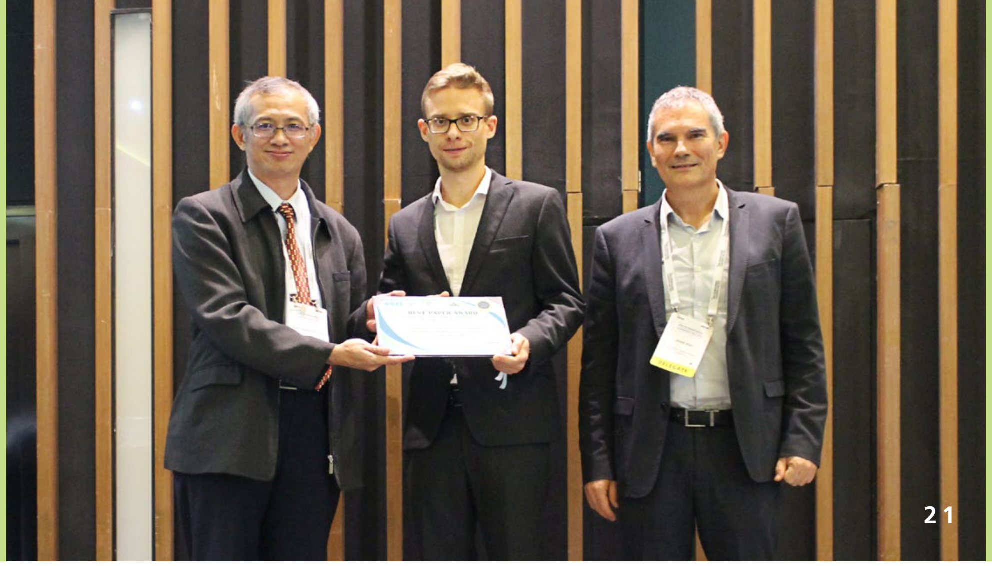
In the hardware test setup, it is verified that using a notch filter in the feedback path of the energy control loop significantly decreases unwanted AC components of the circulating currents within the MMC. Subsequently, the current stress as well as the conduction and switching losses in the semiconductors can be minimized. Furthermore, the dynamic performance of the capacitor voltage estimation and control scheme was analyzed via hardware tests.

17 *Simon Quergfelder from Fraunhofer IISB at the presentation of the EnCN Energy Award at the EnCN Annual Conference 2019. Left in the picture: Christian Zens, Chancellor of FAU. © Energie Campus Nürnberg (EnCN)*

18 *Prof. Eui-Cheol Nho (Pukyong National University, Busan, Korea), General Chair of the ICPE 2019-ECCE Asia, hands over the Best Paper Award – 3rd Prize – for Excellent Academic Performance to IISB employee Benjamin Ruccius. © ICPE 2019-ECCE Asia*

EVENTS

IFEEC 2019 Best Paper Award
LZE Tech Day 2019 gives insights into R&D



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IFEEC 2019 BEST PAPER AWARD

Matthias Schulz, member of the DC Grids group of the Intelligent Energy Systems department of the IISB, is one of the winners of the Best Paper Award of the 4th International Future Energy Electronics Conference IFEEC 2019 in Singapore.

In his publication "A bidirectional and isolated DC/DC inverter connecting mobile battery systems to a DC grid in commercial buildings" Matthias Schulz dealt with a galvanically isolated DC/DC converter for connecting a portable 48 V battery storage to a 380 V DC grid. By means of a newly developed modulation method and a bidirectional energy flow, the topology used enables charging and discharging over the entire range of battery and grid voltage. The implemented control method also allows the storage of the energy contained in the parasitic inductance of a transformer in a capacitor. In addition, soft switching of the power semiconductors on the grid side as well as an increase of the output voltage is now possible. Thus a lower transformation ratio can be selected for the capacitive half bridge with actively clamped and current-fed push-pull output stage and a high efficiency can be achieved.

LZE TECH DAY 2019 GIVES INSIGHTS INTO R&D

On November 7th, 2019, the LZE Tech Day 2019 presented the latest work of the Leistungszentrum Elektroniksysteme (LZE, High-Performance Center for Electronic Systems) to the public and to interested partners from industry. Under the motto "Efficient Electronics – Use Cases, Inspiration, Ideas", examples from every step of the innovation chain were illustrated.

In his keynote speech, Dr. Mathias Glasmacher from Diehl Group talked about the successful MIOTY® communication technology for massive IoT, which is a best-practice example for an extensive and successful market development based on systematic research projects. In addition, scientists working on the different LZE research projects introduced new technologies, close to the stage of commercialization or even at the very beginning of transfer-oriented R&D work. Inbetween the presentations, the LZE forum offered an exhibition including many different partners of LZE and constituted a perfect opportunity for networking. The official program closed with the award ceremony for this year's innovation prize for microelectronics granted by the close LZE partner Förderkreis für die Mikroelektronik e.V.

20 *Prof. Martin März, acting director of Fraunhofer IISB, welcomes the participants of the LZE Tech Day 2019 at Fraunhofer IISB in Erlangen © Kurt Fuchs / Fraunhofer IISB*

21 *In the picture from left: Prof. Huang-Jen Chiu, National Taiwan University of Science and Technology; Matthias Schulz; Prof. Josef Pou, Nanyang Technological University, Singapore, at the Best Paper Award ceremony at the 4th International Future Energy Electronics Conference IFEEC 2019 in Singapore. © ERIAN@NTU / IFEEC*

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GUEST SCIENTISTS

L. Di Benedetto
April 24, 2019 - April 26, 2019
University of Salerno, Italy
Overview on numerical SiC simulation at University of Salerno

H. Luo
July 01, 2019 - September 30, 2019
Tianjin University, China
Photoluminescence spectroscopy characterization of 4H-SiC doping using ion implatation an annealing

S. Ogawa
July 01, 2019 - June 30, 2020
Toray Research Center, Japan
Evaluation of optical LTS for defect characterization of Al-implantation in 4H-SiC

H. Du
September 10, 2019 - March 10, 2020
Aalborg University, Department of Energy Technology, Denmark
Mitigation Strategy for SiC MOCFETs under Short-Circuit Condition

L. Welkin
October 01, 2019 - November 18, 2019
Industrial Technology Research Institute (ITRI), Canada
Research on Battery System with Reconfigurable Battery Array (RAIBA Demonstrator)

X. Guan
October 01, 2019 - May 10, 2019
Tianjin University, China
Determination of effective channel lengths of 4H-SiC 1,2 kV VDMOS devices by electrical evaluation of misalignment structures

Y. Chen
October 01, 2019 - May 10, 2019
Tianjin University, China
Temperature Dependent Point Contact Current Voltage (PCIV) Resistance Profiling of Doped 4H-SiC

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DE102014119386B4

M. Beier, J. Friedrich, C. Reimann, G. Schierning, F. Thiel:
Thermoelektrisches Material und Verfahren zur Herstellung eines thermoelektrischen Materials sowie Verwendung dieses Materials in einem Thermogenerator
DE102018200483B3

M. Billmann, C. Blösch, D. Malipaard, A. Zenker:
Power semiconductor module having layered insulating side walls
Indian Patent 310117

B. Eckardt, S. Matlok:
Umrichter, Vorrichtung mit einem solchen Umrichter, System und Verfahren zum Steuern einer steuerbaren Energiequelle
Inverter, device with such an inverter, system and method for controlling a controllable energy source
Inverseur, dispositif avec un tel inverseur, système et procédé de commande d’une source d’énergie contrôlable
DE502017002248.0
EP3410589B1

T. Erlbacher, A. Hürner:
Monolithisch integrierter Halbleiterschalter, insbesondere Leistungstrennschalter
Monolithic integrated semiconductor, in particular isolating switch
Commutateur à semi-conducteur intégré monolithique, en particulier commutateur de séparation de puissance
United States Patent 10,325,984
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Monolithisch integrierter Halbleiterschalter, insbesondere Leistungstrennschalter
Monolithically integrated semiconductor switch, in particular a power circuit breaker
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Verfahren und Einrichtung zur Energieerzeugung aus wasserstoffreichem Industrie-Abgas
Method and device for generating power from a hydrogen-rich industry exhaust gas
Procédé et dispositif de production d'énergie à partir des gaz industriels riches en hydrogène
DE502016004986.6
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United States Patent 10,218,185

R. Hopperdietzel:
Device for switching a semiconductor-based switch and sensor for detecting a current change velocity at a semiconductor-based switch
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S. Schwanke, C. Reimann, J. Friedrich:
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DE102018206969B3

A. Tobisch:
Verfahren und Vorrichtung zur Messung der Ablenkung von Lichtstrahlen durch eine Objektstruktur oder ein Medium
EP2863167B1

S. Zeltner:
Leistungselektronische Schaltung, leistungselektronischer Energieübertrager und leistungselektronisches Energieübertragungssystem
DE502015009526.1
EP3152824B1

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Minority carrier lifetime measurements on 4H-SiC epiwafers by timeresolved photoluminescence and microwave detected photoconductivity
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S. Bockrath, A. Rosskopf, S. Koffel, S. Waldhör, K. Srivastava, V. R. H. Lorentz:
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First Experimental Test on Bipolar Mode Field Effect Transistor Prototype in 4H-SiC. A Proof of Concept
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Performance of 4H-SIC bipolar diodes as temperature sensor at low temperatures
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A. Diepgen, V. Zimmermann, C. F. Bayer, Y. Zhou, C. Forster, P. Wilbers, J. Leib, A. Schletz, S. Virtanen, M. März:
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A. Erdmann, P. Evanschitzky, G. Bottiglieri, E. Van Setten, T. Fliervoet:
3D mask effects in high NA EUV imaging
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