Fraunhofer

ISIT

FRAUNHOFER-INSTITUT FÜR SILIZIUMTECHNOLOGIE ISIT

Achievements and Results Annual Report 2018

Piezoelectric resonant micro mirrors

Achievements and Results Annual Report 2018

ANNUAL REPORT 2018

NdFeB micromagnets
embedded in silicon

Dr. Axel Müller-Groeling

THE START OF A NEW EPOCH

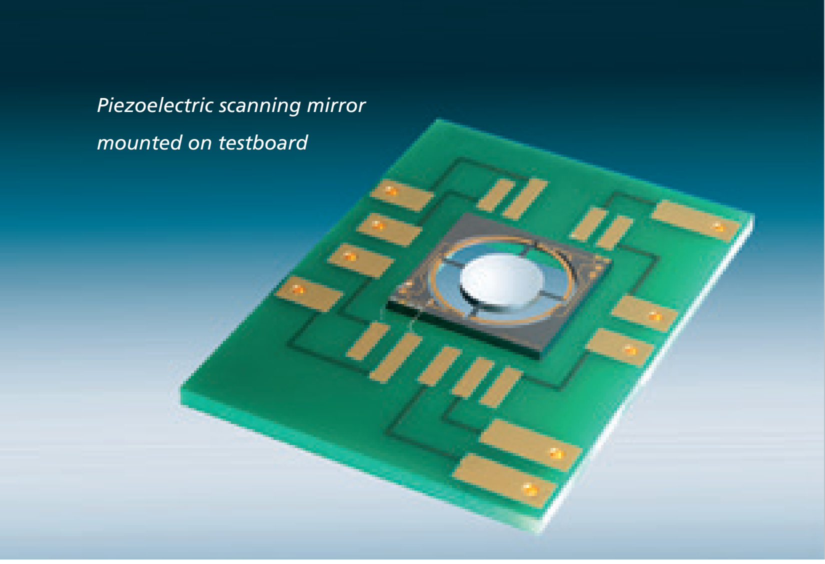
Dear business partners, dear friends of ISIT, dear colleagues,

2018 marked the end of an era at Fraunhofer ISIT. Professor Wolfgang Benecke managed Fraunhofer ISIT for nearly ten years, for the past two and a half years jointly with me. In April Professor Wolfgang Benecke entered his retirement. Through his efforts, he ensured that ISIT is engaged in highly relevant fields of research and development: electromobility, autonomous driving, and the energy revolution are just a few examples. I believe my task is to carry on the successful work that was jointly begun and dedicate my efforts to increasingly making the institute a driving force behind the technology of tomorrow. Against this background, Wolfgang Benecke and I in the initial phase of our joint work began professionalizing the institute's organization. We conducted a comprehensive strategy process at ISIT, aimed at explicitly identifying competencies, services with monetary value, and organizational processes as well as implementing uniform controlling and budget processes at ISIT.

In 2018 we then improved controlling and processes at the institute based on the new strategy, for example by implementing Controlling Boards dedicated to the topics of sales, projects, operations, and innovations. We established a performance figure system and drove the institute's digitalization through various management programs. Now my colleagues and I will intensify business development and sales for the institute in 2019 through concerted market and trend analyses, and considerably accelerate acquisition, also with additional external consultants.

Fraunhofer ISIT achieved a number of outstanding scientific/technical developments over the last few years. The group developed battery systems for specialized applications and an extremely robust, high-performance battery for electromobility. Road vehicles are operated in the partial-load operational range for most of their operating time. The new modular battery system consisting of an extremely robust high-performance battery and responsive, powerful battery electronics delivers the required power reserves for short, power-hungry driving phases.

ISIT developers in the Acoustic Systems and Micro-Drives Working Group together with their colleagues at the Fraunhofer Institute for Digital Media Technology IDMT introduced the first chip micro-speaker on a MEMS basis to the professional community and presented its application for in-ear headphones. MEMS stands for micro-electro-mechanical systems and combines classic semiconductor technology with miniature mechanics in the micrometer range. In this application, the MEMS micro-speakers cover a frequency range from 20 Hz to 20 kHz, generating a



Piezoelectric scanning mirror mounted on testboard

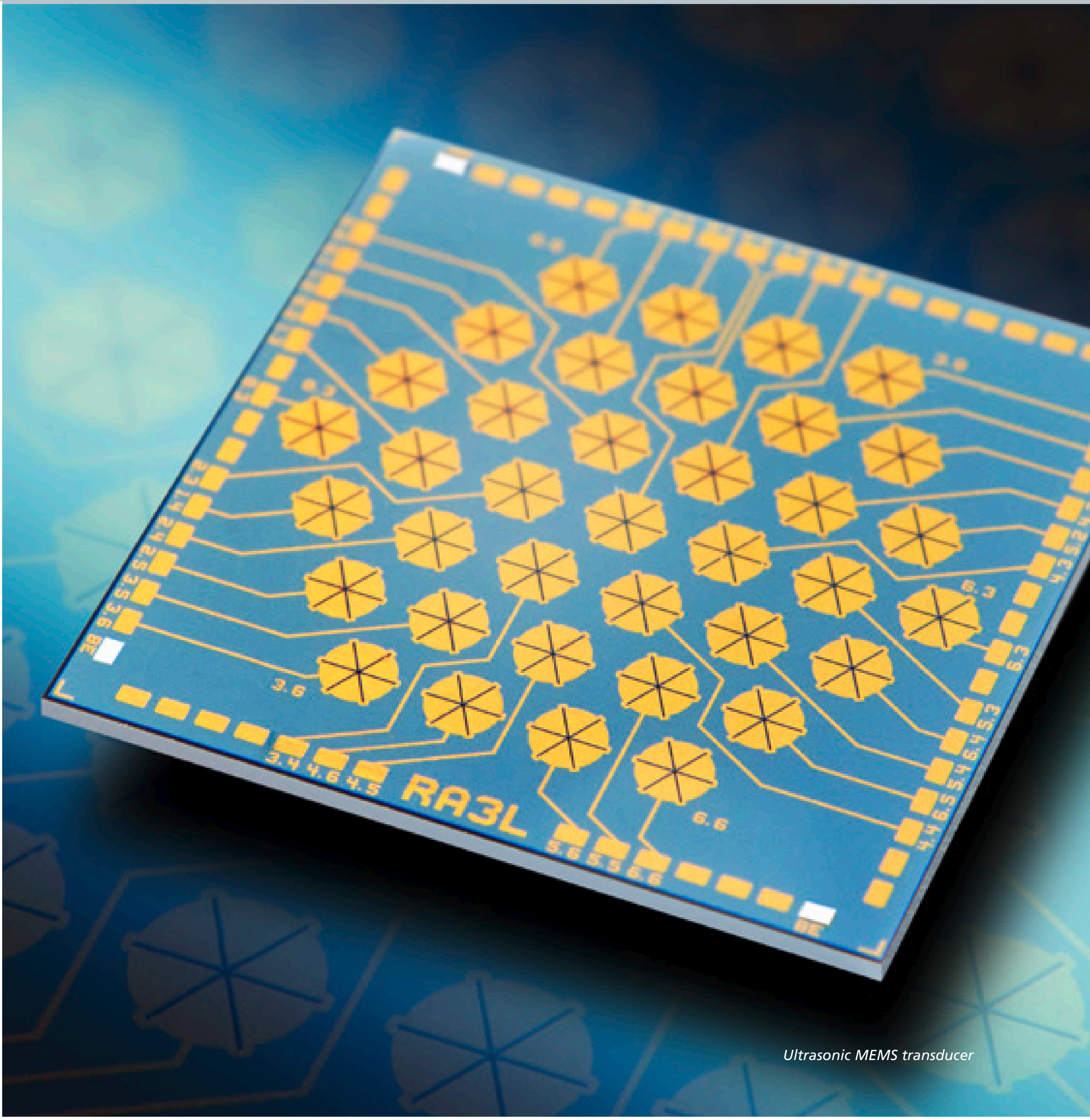
sound pressure level of 110 dB and delivering balanced, powerful sound with brilliant highs. Scientists at Fraunhofer ISIT and Fraunhofer IDMT conducted research for three years in a joint development project. They made a breakthrough in the spring of 2018 and were able to realize high-performance, integrated MEMS speakers, which they now want to bring to market quickly for in-ear applications.

Power Electronics, among the central research topics at Fraunhofer ISIT, have developed into one of the 21st century's key technologies. They guarantee energy efficiency from generation to the consumer, representing crucial leverage for energy conservation through demand-driven energy consumption and the use of renewable energy sources.

The scientists in the High-Efficiency Power Transistors Working Group have succeeded in considerably improving the efficiency, power density, and reliability of the individual components as well as systems through the development of modern semiconductor components. In parallel to developing application-specific components on a silicon basis, Fraunhofer ISIT introduced gallium nitride (GaN) as a new material basis for innovative power semiconductor components. GaN has a number of advantages over silicon for the production of power components. It makes considerably smaller components possible with outstanding electrical characteristics. Fraunhofer ISIT has developed the first diodes and transistors on a GaN basis and presented initial results at electronica 2018. The GaN diodes that were presented, with a cutoff voltage of 160 V, are the result of a joint project involving four Fraunhofer institutes.

All of these developments were made possible with the help of EUR 19.3 million in subsidies for ISIT from the Federal Ministry of Education and Research (BMBF) under the nationwide FMD (Forschungsfabrik Mikroelektronik Deutschland) investment program (also see page 66).

ISIT is also a co-initiator of the major project NEW 4.0 (Norddeutsche Energiewende 4.0) subsidized by the Federal Ministry for Economic Affairs and Energy (BMWi). Around 50 partners from the region and cross-regional partners are conducting a large-scale practical test, linking Schleswig-Holstein with its high-capacity wind energy generating centers and Hamburg with its major energy consumption centers to create an energy region.
NEW 4.0 as a showcase demonstrates that a region with



Ultrasonic MEMS transducer

Top left: X-FAB chairman Rudi de Winter and X-FAB site manager Itzehoe Dr. Werner Riethmüller, top right: Topping-out ceremony for the new X-FAB office building on the Fraunhofer campus, bottom: Daniel Günther, Prof. Isabelle Peters and Dr. Axel Müller-Groeling at the science reception in Itzehoe

Musically underscoring the science reception at Fraunhofer ISIT: Sophienquartett Kiel

4.5 million inhabitants can be reliably supplied with 100 percent renewable energy starting in the year 2035.

Fraunhofer ISIT also initiated a new power electronics network in Schleswig-Holstein at the start of the year. The Ministry of the Economy in Kiel is supporting nationwide networking under the “Landesprogramm Wirtschaft” state economic development program. The major power electronics players in Schleswig-Holstein along with smaller companies are participating in the network on the industry side. They include Danfoss, Vishay, Jenoptik Advanced Systems, Liacon, Fischer + Tausche, Jungheinrich Norderstedt, Nord Drivesystems, Reese + Thies, and Kristronics. Christian-Albrechts University of Kiel, Flensburg University, the universities of applied sciences in Heide, Kiel, and Lübeck as well as the University of Southern Denmark as scientific institutions are contributing their specialized knowledge to the network.

Fraunhofer ISIT generated numerous impulses in 2018 but also has to face new challenges, for example in the job market. The number of applicants responding to our advertisements tells us that we too are affected by the skilled labor shortage. This situation is expected to worsen over the coming years. That is one reason why we want to increase the number of students employed at the institute, from currently around 30–40 to as many as 80, so as to tie students to the institute early on. To this end we have expanded our cooperation with various universities (of applied sciences) in the region, and will establish new relationships with further universities. Thus we also welcome all regional policy initiatives to make Itzehoe more attractive for students and young scientists. We support the city’s efforts to establish a boardinghouse for students to offer low-cost, attractive living space for them while studying in Itzehoe. We also support the state and district plan to build a training center for microelectronics at the Itzehoe location. Feasibility studies are currently under way for both the boardinghouse and the training center.

Naturally we are helping the state of Schleswig-Holstein in the efforts to establish a “Battery Cell Research Factory” contemplated by the federal government in Itzehoe, with a total investment of approximately EUR 500 million, by coordinating the applications and participating in the corresponding committees and sub-projects. We consider the fact that ISIT as one of just eight research institutions nationwide was asked to apply a special honor and a sign that our work is appreciated. This was also the topic of conversation during the visit by the national committee of CDU members of parliament on June 7th during their summer trip. Mark Helfrich, member of parliament for the Steinburg district, issued invitations. The guests were impressed by the variety of activities in the field of storage technologies and the energy revolution, and saw Hightech Itzehoe as an excellent location for future projects of the Fraunhofer-Gesellschaft.

ORGANIZATIONAL CHART

Head of Institute
Dr. Axel Müller-Groeling *Director*
Prof. Dr. Bernhard Wagner *Deputy Director*

Coordination of Forschungsfabrik Mikroelektronik Deutschland (FMD)
Prof. Dr. Bernhard Wagner

Business Units

Management-Center
Karin Dusil

Business Support and Optimization

Administration

Power Electronics (PE) Prof. Dr. Holger Kapels	**Micro Manufacturing Processes** Christian Beckhaus	**MEMS-Applications**** Dr. Fabian Lofink
Advanced Power Transistors	*WL Packaging and Processes*	*Optical Systems*
*PE for Renewable Power Systems**	*Validation and Pilot Production*	*Acoustic Systems and Microactuators*
Battery Systems for Special Applications	*Module Services*	

Technology-Development
Dr. Oliver Schwarzelbach

MEMS Fabrication
Dr. Mohammad Hejjo al Rifai

* Application Center Hamburg
** with an external office at CAU Kiel

Prof. Ralf Dudde (2nd from left) explains the research work of Fraunhofer ISIT in the cleanroom

Digitalization was on the agenda for the scientific reception on May 31st at Fraunhofer ISIT in Itzehoe under the auspices of Premier Daniel Günther. Over 150 guests at the reception included newly appointed university professors, heads of the non-university research institutions, scientists in the field of digitalization, and representatives of the university executive committees and students as well as university councils. We were very pleased that the state government chose our institute for the reception, emphasizing the great importance of ISIT for the state.

The expansion of the high-tech site progressed considerably last year as well. X-FAB MEMS Foundry Itzehoe, an important strategic partner of Fraunhofer ISIT, constructed a new office building directly next to the institute – a clear and important commitment by X-FAB to the Itzehoe site. The new two-story building costing three million euros provides office space for 84 employees along with various storage rooms. X-FAB produces micro-systems on an industrial scale in Itzehoe, for instance for the automobile industry and medical engineering, in fruitful cooperation between ISIT and X-FAB. The market offerings of both X-FAB and Fraunhofer ISIT are considerably strengthened for external customers through mutual references.

After more than twenty years of development, ISIT is currently in the midst of a generation change. Colleagues who conceived and built up ISIT starting from Berlin are reaching retirement. This applied to a number of colleagues aside from Professor Benecke in 2018. I am mentioning one as a representative for all of them: Dr. Gerfried Zwicker. He contributed significantly to the development of ISIT in Itzehoe in a management position. I would like to thank him and all other retired employees for their successful contribution to ISIT and the Fraunhofer-Gesellschaft.

Naturally I also thank all the ISIT staff, all colleagues, for their dedication, commitment, and especially their willingness to blaze new trails with us, which is indispensable for any leading organization to maintain its position.

A. Müller-Groeling

Dr. Axel Müller-Groeling

FRAUNHOFER-INSTITUT FÜR SILIZIUMTECHNOLOGIE (ISIT)

Research and Production in One Location

The Fraunhofer Institute for Silicon Technology ISIT develops and produces power electronics and microsystems according to customers specifications. Important areas of application include energy technology, automotive and transport engineering, the consumer goods industry, medical technology, communications technology, and automation. Ultra-modern technological equipment based on 200 mm silicon wafer technology and expertise built up over decades put Fraunhofer ISIT and its customers at the forefront of the field worldwide.

Fraunhofer ISIT supports customers right the way from design and system simulation to the production of prototypes, samples, and preparation for series production. The institute currently employs a staff of 160 persons with engineering and natural sciences backgrounds. Fraunhofer ISIT deals with all the important aspects of system integration, assembly and interconnection technology (packaging), and the reliability and quality of components, modules, and systems. The institute also provides manufacturing support for application-specific integrated circuits (ASICs) to operate sensors and actuators. Activities are rounded off by the development of electrical energy storage devices, with a focus on Li-polymer batteries.

One thing that really sets Fraunhofer ISIT apart is the speed with which it can transfer innovative developments into industrial application and production. To this end, Fraunhofer ISIT operates a wafer production line in its cleanrooms in collaboration with the companies Vishay and X-FAB MEMS Foundry Itzehoe. There are longstanding collaborations with a variety of manufacturing companies local to Fraunhofer ISIT.

The quality management system at Fraunhofer ISIT is qualified according to ISO 9001:2015. Fraunhofer ISIT runs an application center at Hamburg University of Applied Sciences, a project group at the University of Applied Sciences in Heide, and a working group at the Christian-Albrechts-Universität in Kiel.

Cooperation with Fraunhofer ISIT

The institute's services assist companies and users in a wide range of sectors. Components, systems, and production processes are developed, simulated, and implemented in close collaboration with customers. This process is aided by Fraunhofer ISIT's use of technology platforms – production process flows defined for whole groups of components – meaning they can be used in production unchanged or with simple modifications to the design parameters. Fraunhofer ISIT's expertise presents particularly exciting possibilities for small and medium-sized enterprises looking to realize their technological innovations.

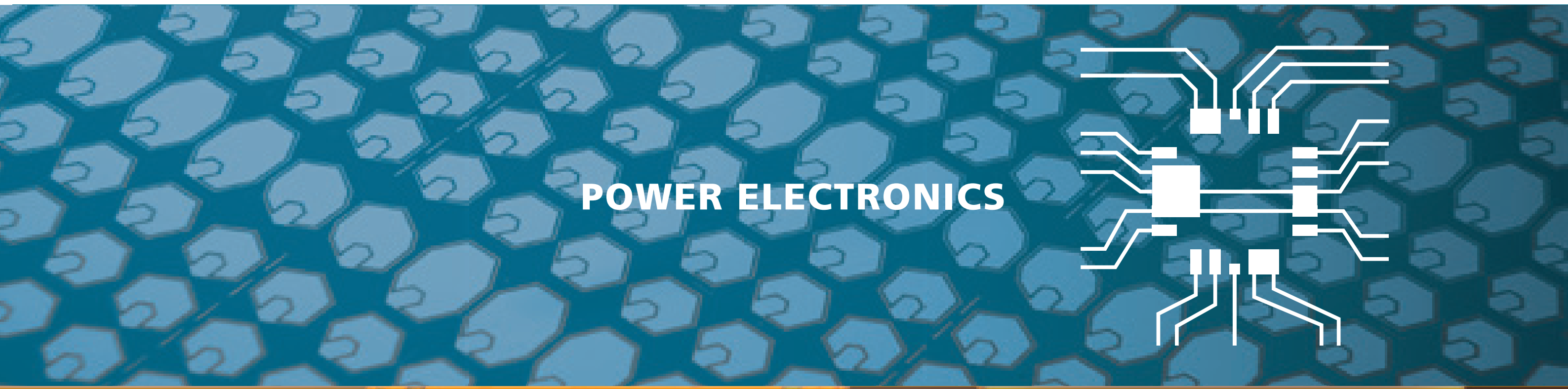
Fraunhofer ISIT is Participant of Research Fab Microelectronics Germany

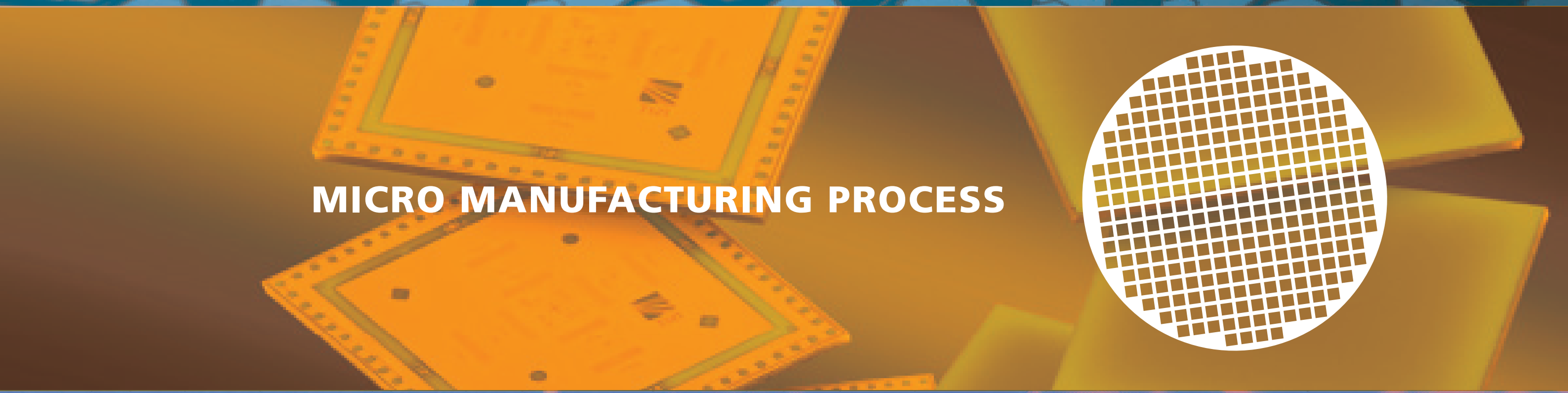
To reinforce the position of Europe's semiconductor and electronics industry within global competition, eleven institutes within the Fraunhofer Group for Microelectronics - including the Fraunhofer ISIT - have, together with the Leibniz Institute for Innovations for High Performance Microelectronics (IHP) and the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH), come up with a concept for a cross-location research factory for microelectronics and nanoelectronics. In spring 2017, this new organization got off the ground. The concept for the research fab was designed jointly by Fraunhofer and Leibniz to combine their competences in a pool for technologies. For the modernization and extension of their equipment the 13 research facilities receive around 350 million euros from the Federal Ministry of Education and Research. The investments for the Fraunhofer ISIT amounting to 19.3 million euros serve to modernize and expand the cleanroom equipment with a focus on power electronics and novel sensor systems.

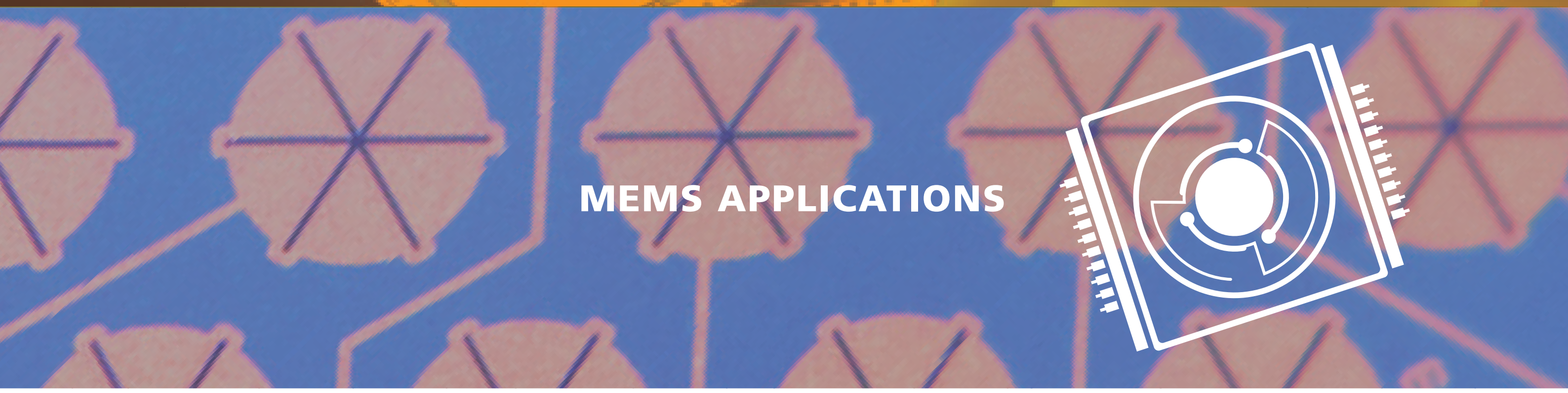
In power electronics, ISIT will provide facilities for the development of gallium nitride as a new material base for innovative power devices that did not previously exist at the institute. New systems are also being purchased for the development of sensors and actuators, for example equipment for applying piezoelectric and magnetic materials to silicon, vapor deposition systems for special optical and infra-red coatings and furnace systems in which glass wafers can be viscously shaped specifically.

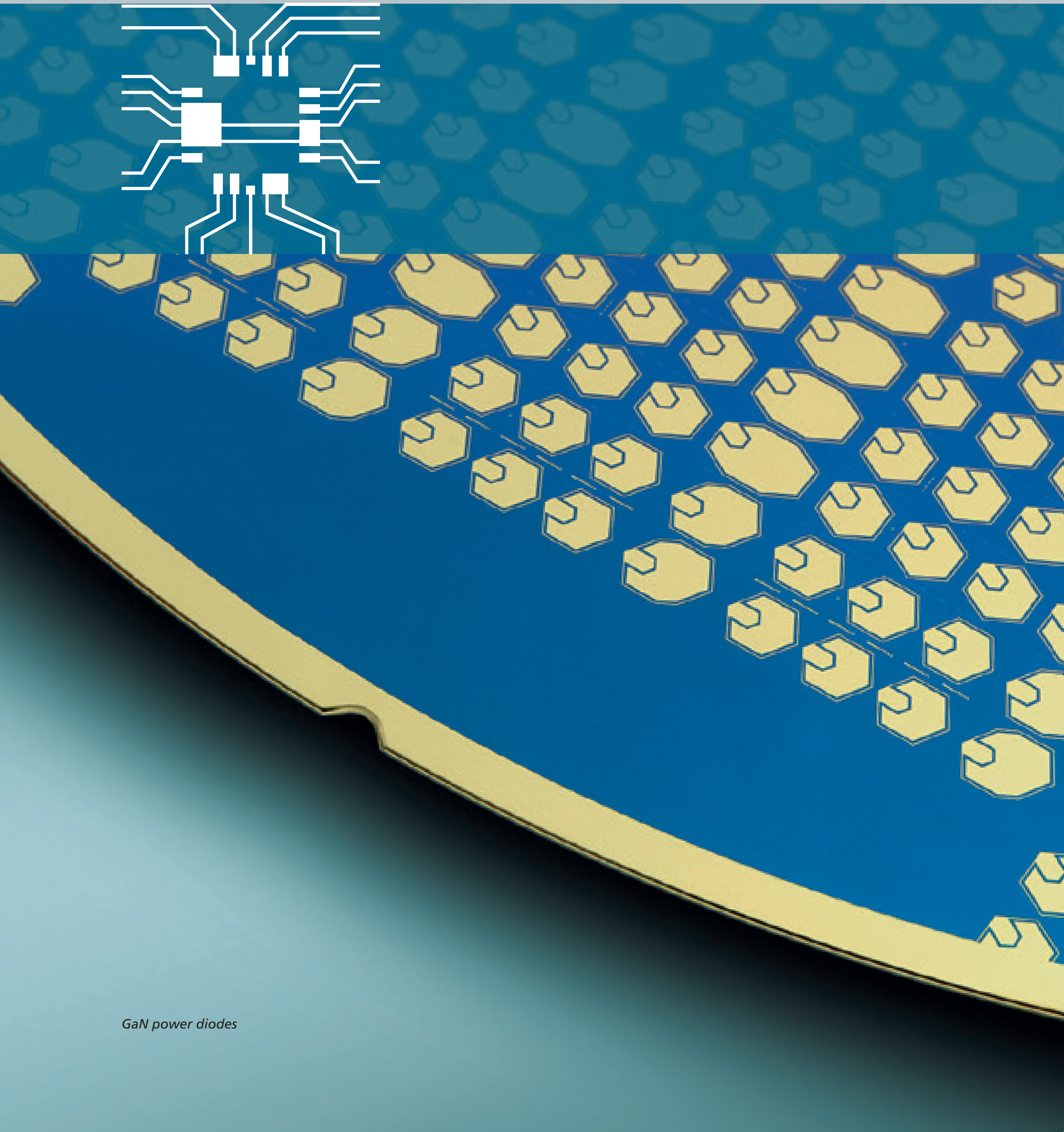
With this new equipment park, ISIT can offer forward-looking manufacturing processes to the industry and is able to develop novel components and convert them into production.

BUSINESS UNITS



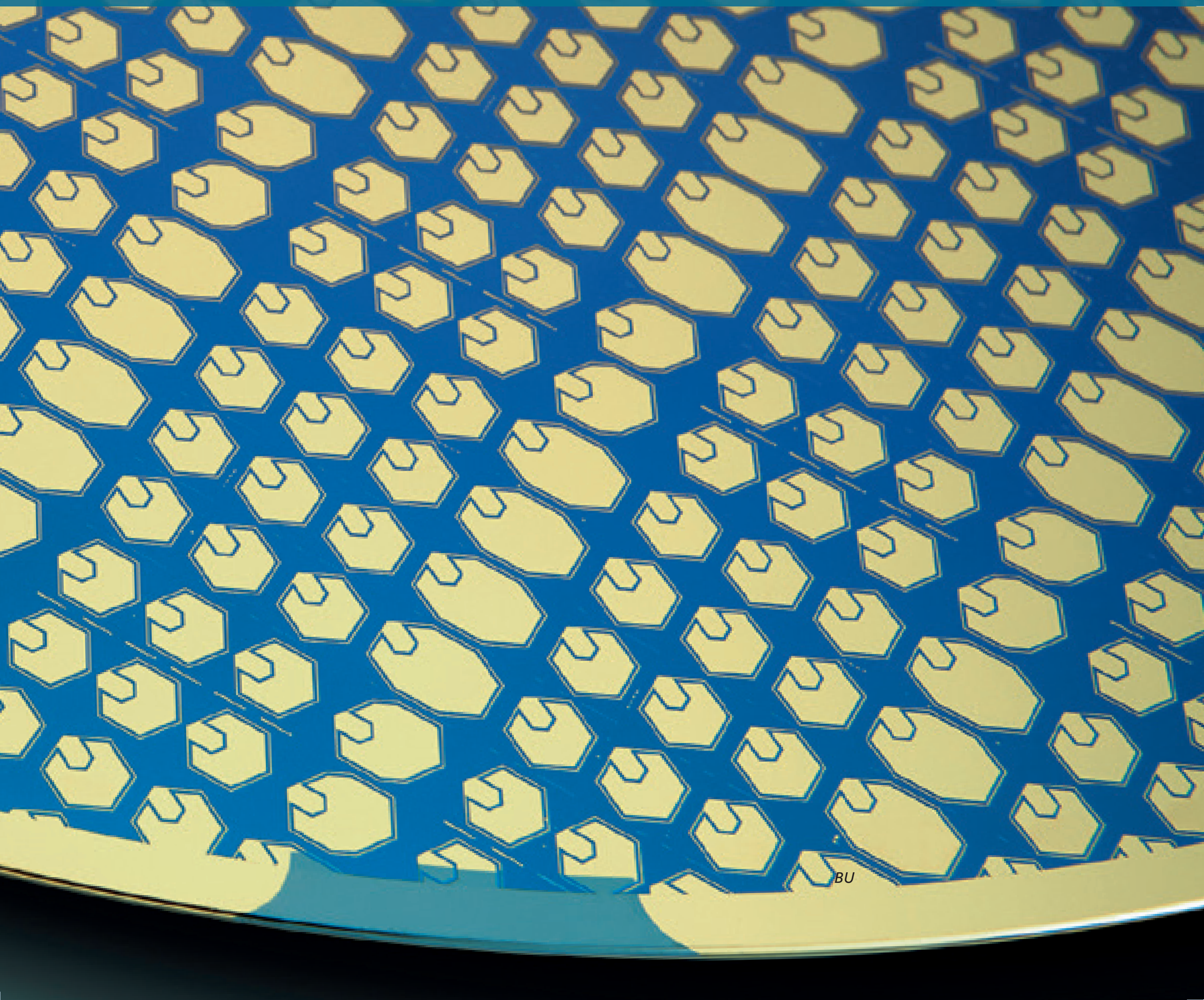


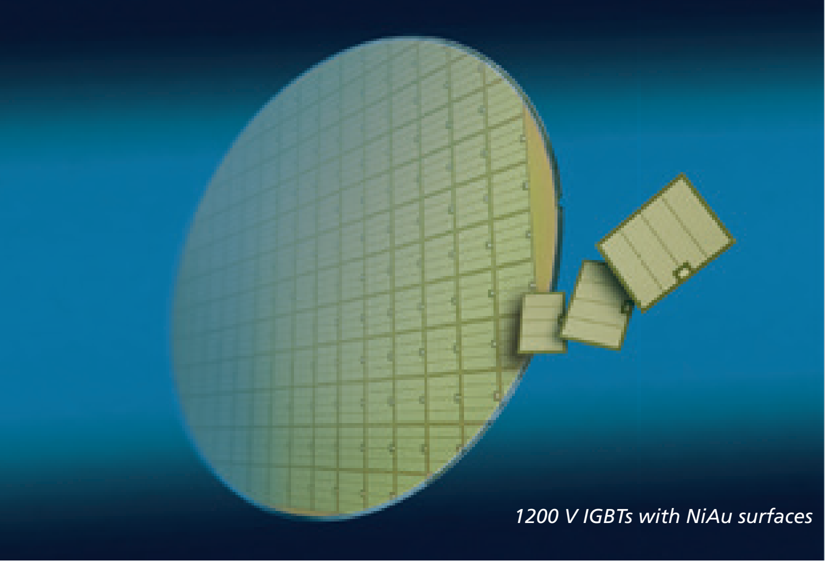




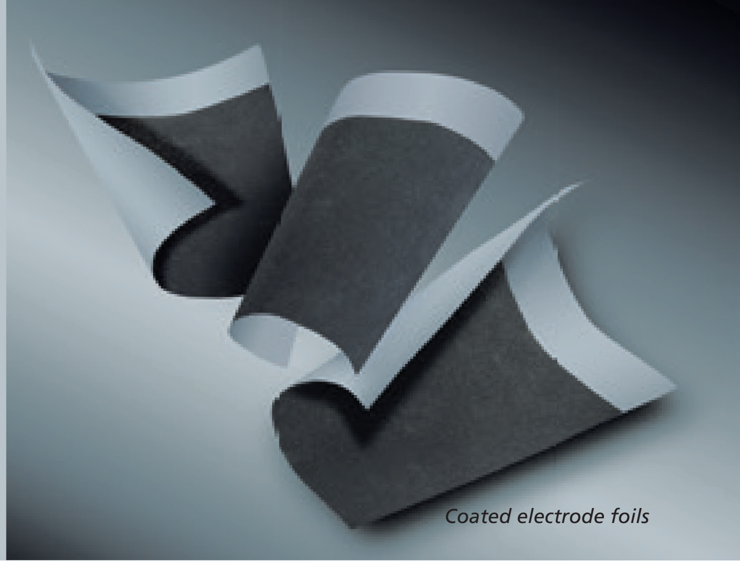
GaN power diodes

POWER ELECTRONICS





1200 V IGBTs with NiAu surfaces



Coated electrode foils

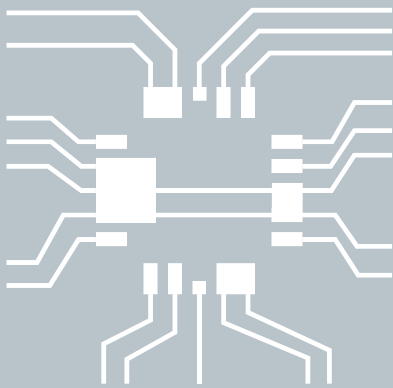
Development of Technologies, Components and System Concepts for High-Performance Energy Systems

The Business Unit Power Electronics at Fraunhofer ISIT develops and manufactures innovative active and passive power semiconductor components based on silicon and gallium nitride, develops power electronic systems and integrates them with high-performance accumulators for special applications towards high-power storage systems.

The advanced power transistors and diodes from Fraunhofer ISIT supporting applications in a wide voltage range from a few 10 V to 1200 V. The development portfolio ranges from silicon-based IGBTs, diodes and MOSFETs to diodes and transistors for highest switching frequencies in the MHz range based on gallium nitride, using modern 8″ manufacturing environment. A particular R&D focus is the application-specific design of the components and the development of new device architectures. Another important research topic is the development of new processes for advanced power device designs on wafer-level. For gallium nitride devices, ISIT is developing also front and back side contacting methods for bulk-GaN wafer and GaN-on-Si wafers. The Fraunhofer ISIT develops customer-oriented device structures with special pad configurations and for improved integration concepts. For the wafer handling and wafer processing of thin Si substrates, the ISIT developed and applied new carrier wafer concepts together with laser annealing processing. The laser annealing enables the dedicated doping activation allowing customer-specific optimizations of static and dynamic losses while improving the robustness of the components. These activities are supported by numerous simulations, design and test tools. Additionally, the Fraunhofer ISIT has many years of R&D experience in the design and manufacturing of CMOS circuits.

The development of passive electronic components focuses primarily on chip capacitors, precision resistors and inductors as well as corresponding chip-level circuit networks. This involves the evaluation of new materials as well as their implementation in existing process flows.

On system level, the ISIT offers the development of novel circuit topologies and integration concepts for highly efficiency DC/DC and DC/AC power converters using application-specific power semiconductors targeting an optimized overall system performance and long-term reliability. By using resonant circuit topologies and control techniques, peak efficiencies larger than 99% are realized and a soft-switching operation is achieved over nearly the entire output power range.
For the increase usage of renewable energies, the ISIT develops solutions for increased flexibility for the overall grid



BUSINESS UNIT POWER ELECTRONICS

stability by using the specific possibilities of battery systems. Furthermore, the ISIT is investigating how new control methods can be used to provide important system-stabilizing services and supports the overall system simulation. The main areas of application for these services of ISIT are in the field of regenerative energies, e-mobility and electric flying.

The topic of energy storage has been for a long time one of the key research areas at Fraunhofer ISIT. The ISIT develops batteries and battery systems for a wide variety of applications with its specific requirements, e.g. a particularly high energy density for a long range in electric vehicles or a high power density to charge and discharge batteries quickly. The latter is of particular interest in the storage of wind energy for grid stabilization. By this, it is possible for the ISIT to realize battery systems for special applications, where for instance stability at high temperatures or a particularly high power density is necessary. In the activities, the Fraunhofer ISIT pays special attention to a production-related development.
At the ISIT, a complete process chain is available from paste processing up to the assembly and characterization for single cells up to high-power storage systems. The complete process chain from paste preparation and electrode production to packaging and electrical and thermomechanical characterization of cells of different chemistry and design is available.
A current focus is on the development of special high-performance batteries that can be charged in less than four minutes and deliver all their energy when needed in one minute. In addition, the Fraunhofer ISIT is researching next generation of energy storage systems, e.g. lithium-sulfur battery, which can be expected in the future, a significant increase in energy density at the same time significant cost reduction.

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VERTICAL GALLIUM NITRIDE POWER DEVICES

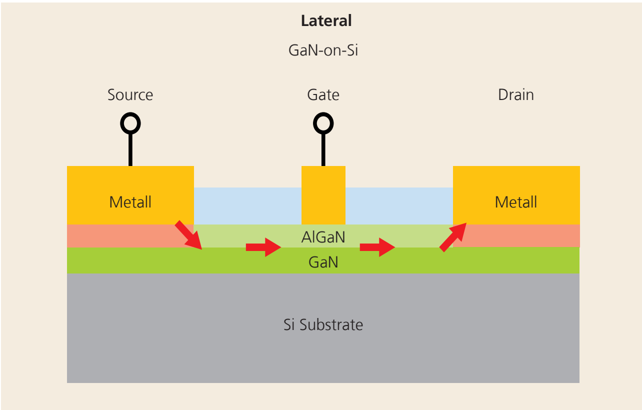


Figure 1a: Schematic of a lateral GaN HEMT device; red arrows show the current path

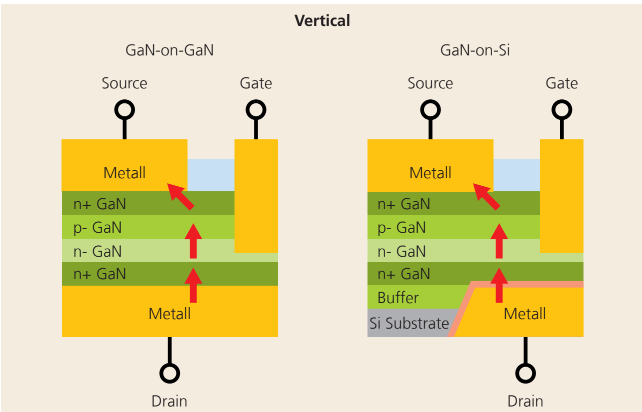


Figure 1b: Schematic of vertical GaN devices; red arrows show the current path

Project name:	Vertigo (Fraunhofer MaVo Programm)
Duration:	03.2017–03.2020
Partners:	Fraunhofer IAF, Freiburg, Fraunhofer ISIT, Itzehoe, Fraunhofer IISB, Erlangen, Fraunhofer THM, Erlangen

The group Advanced Power Transistors at the Fraunhofer ISIT combines the expertise of Silicon-based power devices and MEMS process technologies with the fast growing field of wide bandgap semiconductors. The applications for the new vertical gallium nitride (GaN) power devices range from 48 V vehicle applications up to point of load (POL) converters for data centers. Vertical GaN power devices enable higher current densities, increased efficiencies and more compact designs. The Fraunhofer ISIT develops vertical diodes and transistors in the 200 V voltage class, manufactured on a 200 mm GaN-on-Si platform at the ISIT.

One Step Further

State of the art GaN devices are lateral HEMTs (High Electron Mobility Transistor) using the 2D electron gas effect (see figure 1a). The Fraunhofer ISIT is developing vertical devices structures (see figure 1b) to release the full potential of the wide bandgap semiconductor material GaN such as a higher switching speed and an improved RDS(on)/ VBR(DSS) – ratio, compared to Silicon. The cooperation within the "Forschungsfabrik Mikroelektronik Deutschland" (FMD) enables a process line from the base material up to the device manufacturing.
Also other 8 inch substrates from other suppliers can be used for the device processing in the ISIT cleanroom.

Results

As a first step, vertical pin-diode devices (see figure 2) have been developed and realized. Necessary base processes like ohmic contacts on p-type and n-type doped GaN layers (see figure 3) with contact resistances after metallization and rapid thermal annealing (RTA) in the range of 10^{-6} Ωcm² were developed.

The breakdown voltage of the diodes is near the goal of 200 V (see figure 5). The junction voltage drop is approx. 2.3 V (see figure 6). Currently, the Fraunhofer ISIT is working on the development of vertical GaN transistor devices.

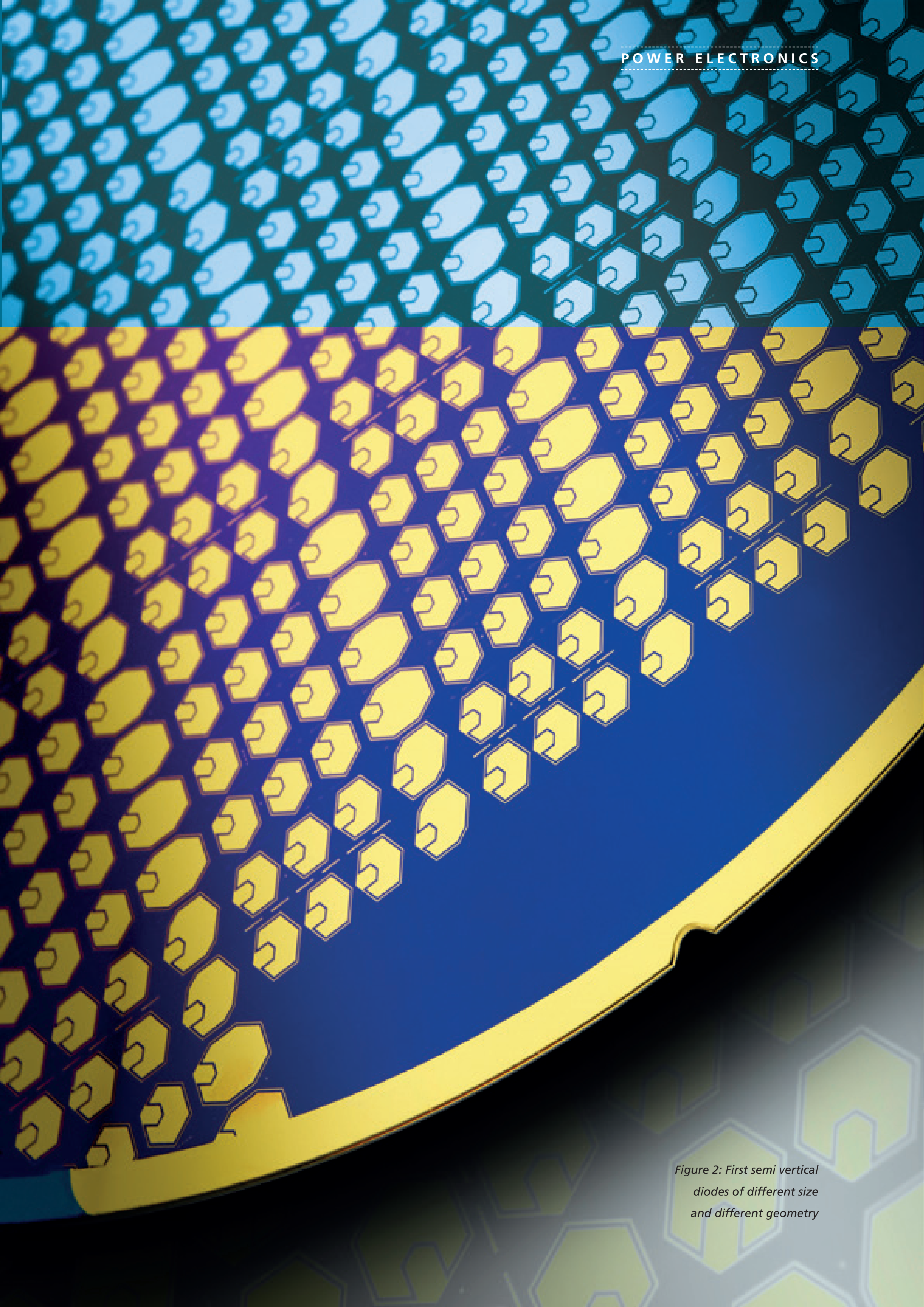
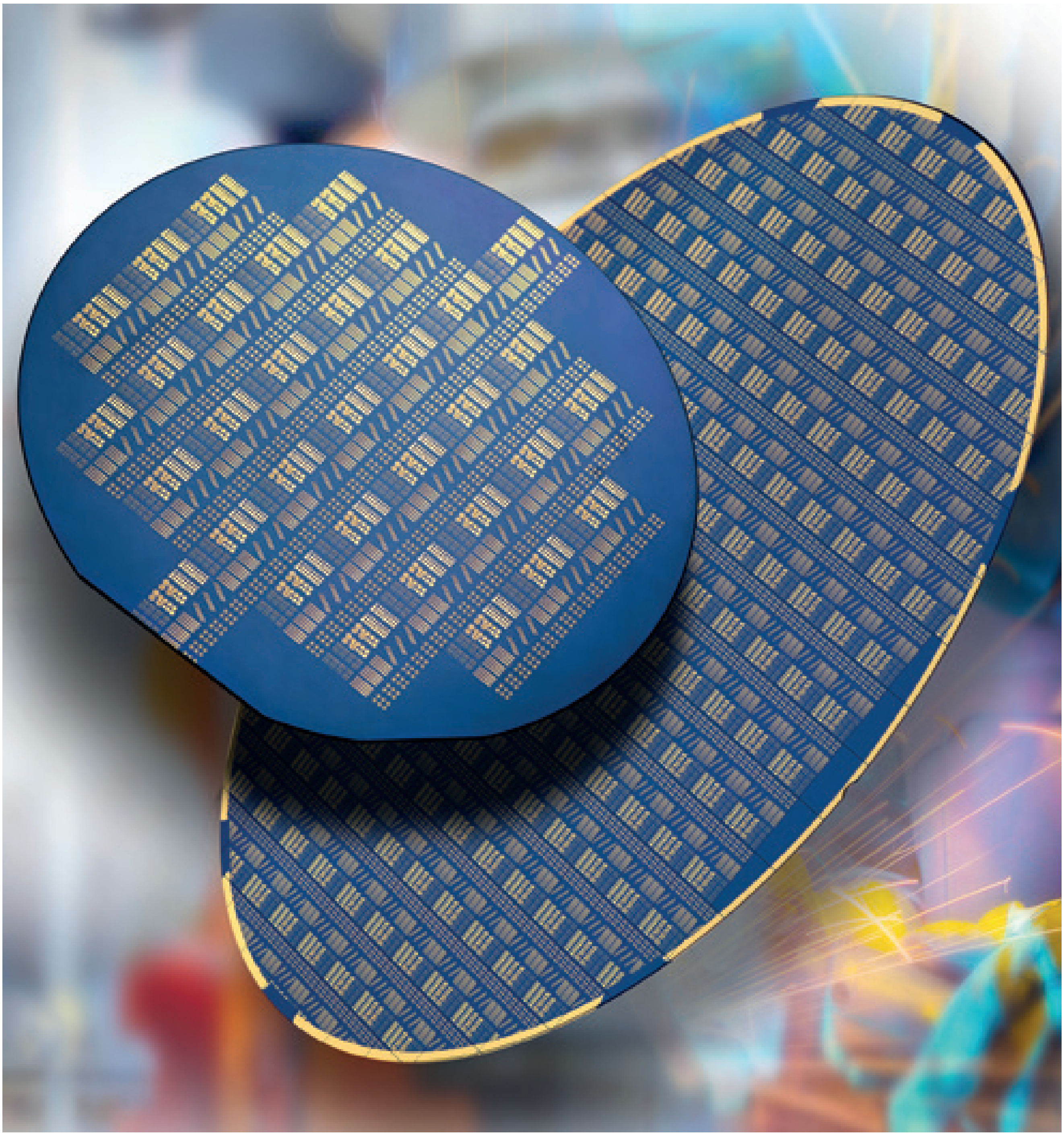


Figure 2: First semi vertical diodes of different size and different geometry

Figure 3: GaN on Si, 4-inch and 8-inch wafer, test structures for measurement of n-type and p-type contact



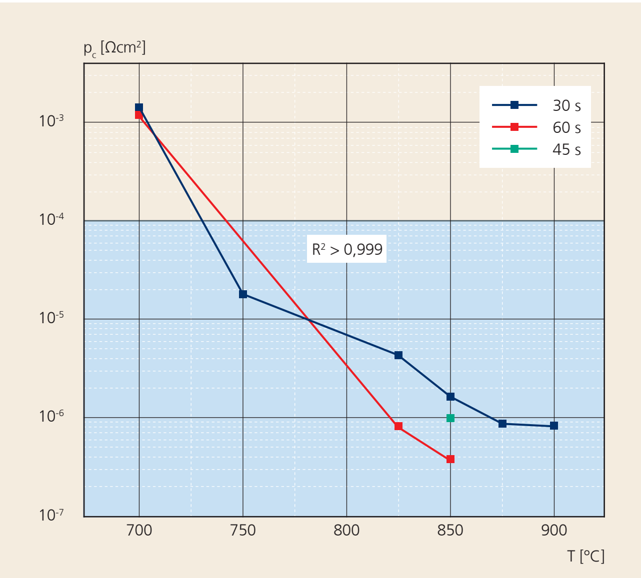


Figure 4: Contact resistance vs. temperature for an annealing time of 30 sec, 45 sec and 60 sec between metal and n-type GaN

What we Offer

At Fraunhofer ISIT we offer the complete development chain for vertical GaN based semiconductors. That includes simulation of devices, processing, electrical measurement and characterization of the devices as well as analytical techniques, e.g. SEM or FIB. For the developing and manufacturing process, a 200 mm Silicon on GaN technology and equipment park is available within the clean room. The developed process and the equipment can subsequently be used for a pilot production at Fraunhofer ISIT.

Authors: Frank Dietz
Heiko Züge

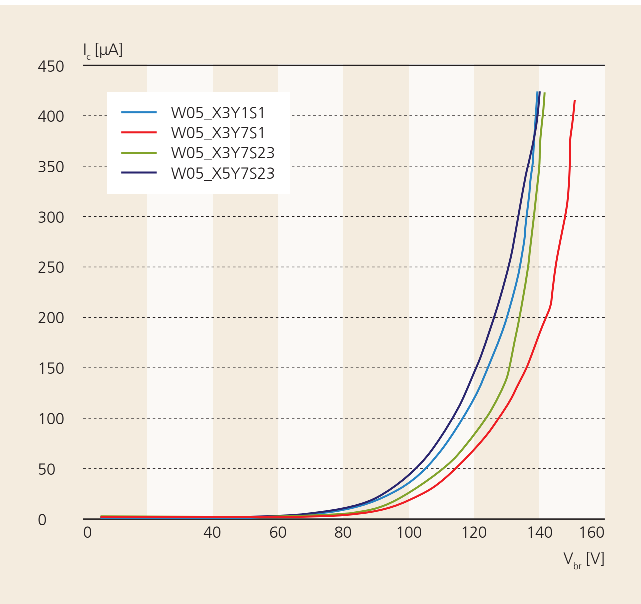


Figure 5: Breakdown voltage (V_{br}) of semi-vertical GaN devices of different size and different geometry

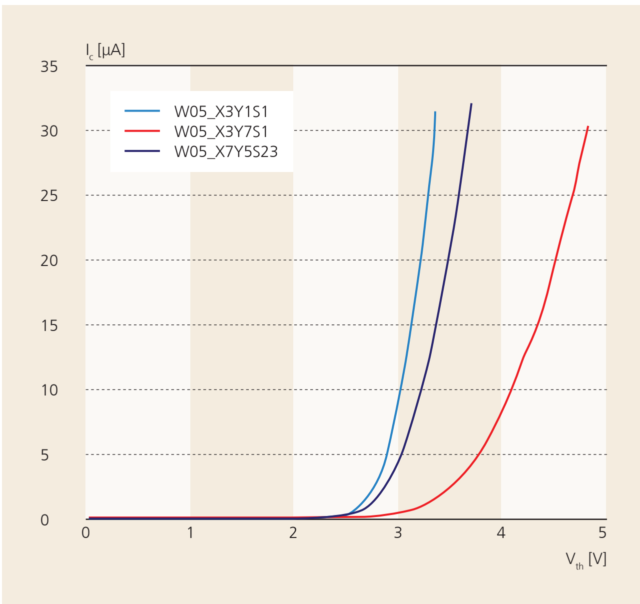


Figure 6: Threshold voltage (V_{th}) of semi-vertical GaN devices of different size and different geometry

HIGHLY EFFICIENT SIC MOSFET INVERTER WITH MODEL-BASED CONTROL

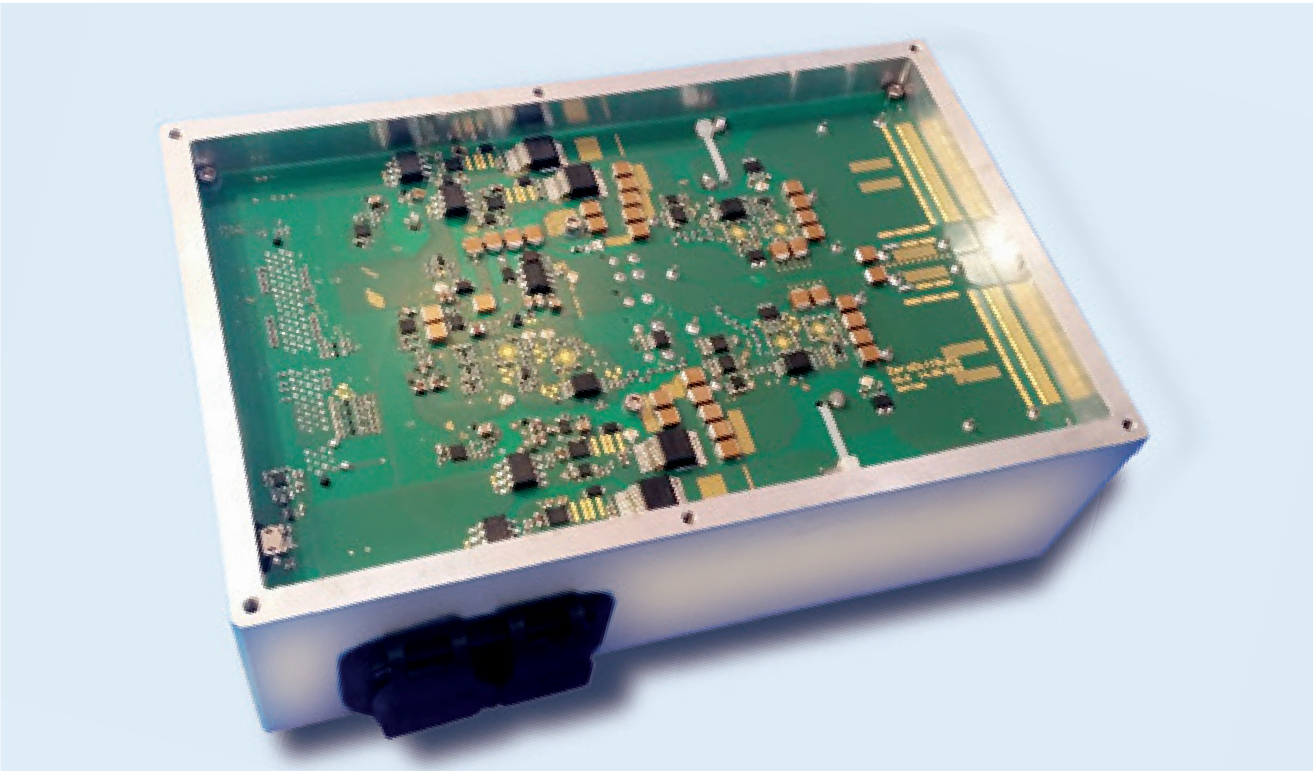
With the energy transition agenda in the European power sector, there is an increase in the importance of the decentralized generation, distribution, conversion and provision of electrical energy. The same holds true for electric vehicles and the corresponding charging infrastructure.

Power electronic converters are key enablers to facilitate this transition, increasing the amount of renewable energy sources coupled to the grid. Inverters form an indispensable link between DC and AC voltage to be fed into the power grid or to drive electrical motors. In the course of digitalization, fast processing power becomes widely available, enabling the implementation of more sophisticated control schemes at higher speeds. This allows pushing the boundaries of efficiency, power density and reliability. The application center power electronics for renewable energy systems possesses the expertise in state of the art bidirectional inverters, DC/DC power converter topologies, hardware design, control strategies and efficient microcontroller implementation.

Efficiency vs. Power Density

The seamless integration of renewable energy systems into the grid is one of the key drivers for the development of power electronics. Efficiency, reliability and power density are especially relevant not only in the power grid, but also in mobile applications, like electric vehicles or drones.
With the miniaturization of electronics, the magnetic and cooling components, determine the weight and volume of

Figure 1: 2.5 kW inverter prototype



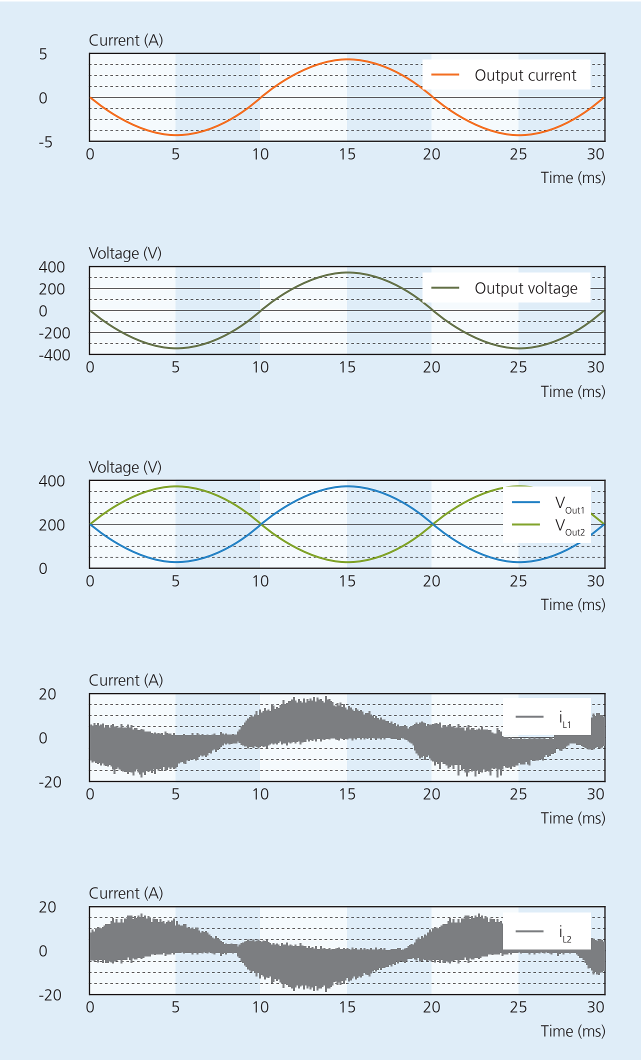


Figure 2: Measured output voltage and frequency modulated inductor currents

inverters. On the one hand, increased switching frequencies are desirable in order to decrease weight and volume of passive components. On the other hand, higher frequencies introduce additional switching losses, which in turn degrade efficiency. This leads to the typical design trade-off: efficiency vs. power density.

Soft Switching by Frequency Modulation

The improved switching behavior of wide bandgap semiconductors together with soft-switching operation can drastically reduce switching losses. This allows for a more compact construction and high switching frequencies while maintaining high efficiencies. This technology is driven by the constant development of new powerful microcontrollers that enable the implementation of fast and complex control.

Novel Control Concept

Based on the experience with highly efficient soft-switching DC/DC converters, patented by the application center (Patent no DE102015219850A1), a novel inverter concept has been developed.

This new approach can maintain the wide range soft-switching property of the DC/DC converter, while being able to produce clean sine waves with very low harmonic distortion. This property is based on the modulation of the switching frequency and duty cycle depending on the operating point, which is far more complex for an inverter compared to a DC/DC converter. The key aspect of this novel control concept is the use of model-based and optimal control theory, which together with classical gain scheduling, enables the developments of an adaptive linear quadratic Gaussian (LQG) controller that takes care of the frequency modulation.

Prototype Results

The novel inverter concept has been successfully implemented and tested on a 2.5 kW prototype with SiC MOSFETs and switching frequencies modulated in the range of 30 – 400 kHz.

Figure 3: Grid connected PV plant

Figure 4: Battery electrical storage system for frequency stabilization

The prototype output exhibits very low total harmonic distortion (THD). Thus, there is no need for further line filters when operated as a grid tied inverter. The clean sine waves are also beneficial for operation as a drive inverter. In comparison to conventional two or three level drive inverters, the voltage stress on the motor windings isolation is drastically reduced, preventing premature failure.
The efficient controller implementation enables current loop cycle times of only 11 µs, allowing for a very fast dynamic response of the entire control system. As a result the fully soft switched operation is maintained for a wide range of load conditions.

DC/AC Inverter Prototype Specification	**High Efficiency, Bidirectional[2] DC/AC-Inverters**
• Max. Power: 2.5 kW • Target Peak Efficiency: >99%[1] • Input/ battery DC voltage: 400 V • Flexible output AC voltage: up to 230 V • Switching frequency: 30–400 kHz • Single-phase non isolated output • Passively cooled	• Model-based control with MPPT and observer based state feedback • Soft-switching by modulation of frequency and duty cycle • Fast output current control loop (11 µs) • Low THDI output current control • Measured THDI range of 1.33–4.81% (operating point dependent)

[1] Excluding MPPT tolerance

[2] Not implemented as of March. 2019

Conclusion

With the successful implementation of the novel control concept on a SiC MOSFET based inverter an important milestone has been reached.
As a result, a new converter platform has been developed with a number of advantages:

- high efficiency due to soft-switching operation
- increased lifetime due to decreased stress on semiconductors or motor winding isolation
- reduced filtering requirements (low THD output sine waves)
- flexibility by a high efficiency over wide operating range
- fast dynamic response for new applications like fast frequency response

Since the founding of the application center, major progress has been achieved in the fields of device characterization, lifetime prediction, design and customization of DC/DC and DC/AC converters. Future development will focus on:

- grid integration & synchronization
- 3 phase topologies for higher power grid and motor driver applications.
- higher power density

Authors: Felix Manthey,
Henri Zeller,
Eivind Langnes

TAILOR-MADE BATTERY SOLUTIONS FOR HIGH POWER APPLICATIONS

The department „Batteries for Special Applications“ of Fraunhofer ISIT has been working in the field of electrochemical energy storage since 1999 and addresses central subjects with its areas of expertise. A complete process chain for producing Lithium secondary cells with patented variable chemistry and design technologies is therefore available. This includes the transfer and up-scaling of laboratory processes to industrial standard.
One of the main working fields of the research group is the further development of existing accumulator systems as well as research and adaptation of novel concepts.
The main focus is on new materials, new material formulations for electrodes, novel electrolyte systems and separators.
Further work includes advanced manufacturing processes leading to an improvement of cell performance, lowering of costs and/or reduction of detrimental effects on the environment.
Beyond that, activities are also guided by the need to customize lithium cells for different fields of application.
In particular, this refers to optimization of parameters as energy density, power density, cycle stability, long life-time, intrinsic safety as well as the adaption for special conditions of operation. The "pouch-cells" developed by the Fraunhofer ISIT enable flexibility of design in terms of size and shape to match exactly the space requirements for the cells and cell modules.

Results

A view at the functions required in connection with hybridization of vehicles, such as the recuperation of braking energy, support during acceleration processes („boost function“) and sailing, makes it clear that the requirements placed on the short-term performance of the 0.25–1.5 kWh energy-capable storage units are quite considerable. Depending on the system requirements and design, the short-term power peaks range between 10–20 kW, for which charging rates of more than 10 C are required. Usually a significant increase of the power of lithium ion battery cells goes hand in hand with a loss of power density. In order to break this connection, Fraunhofer ISIT developed a new cell starting with an adapted chemistry and including optimized cells geometries. The new cell is able to be charged and discharged at 10 C and provides at the same time an energy density of above 150 Wh/kg.

Equipment

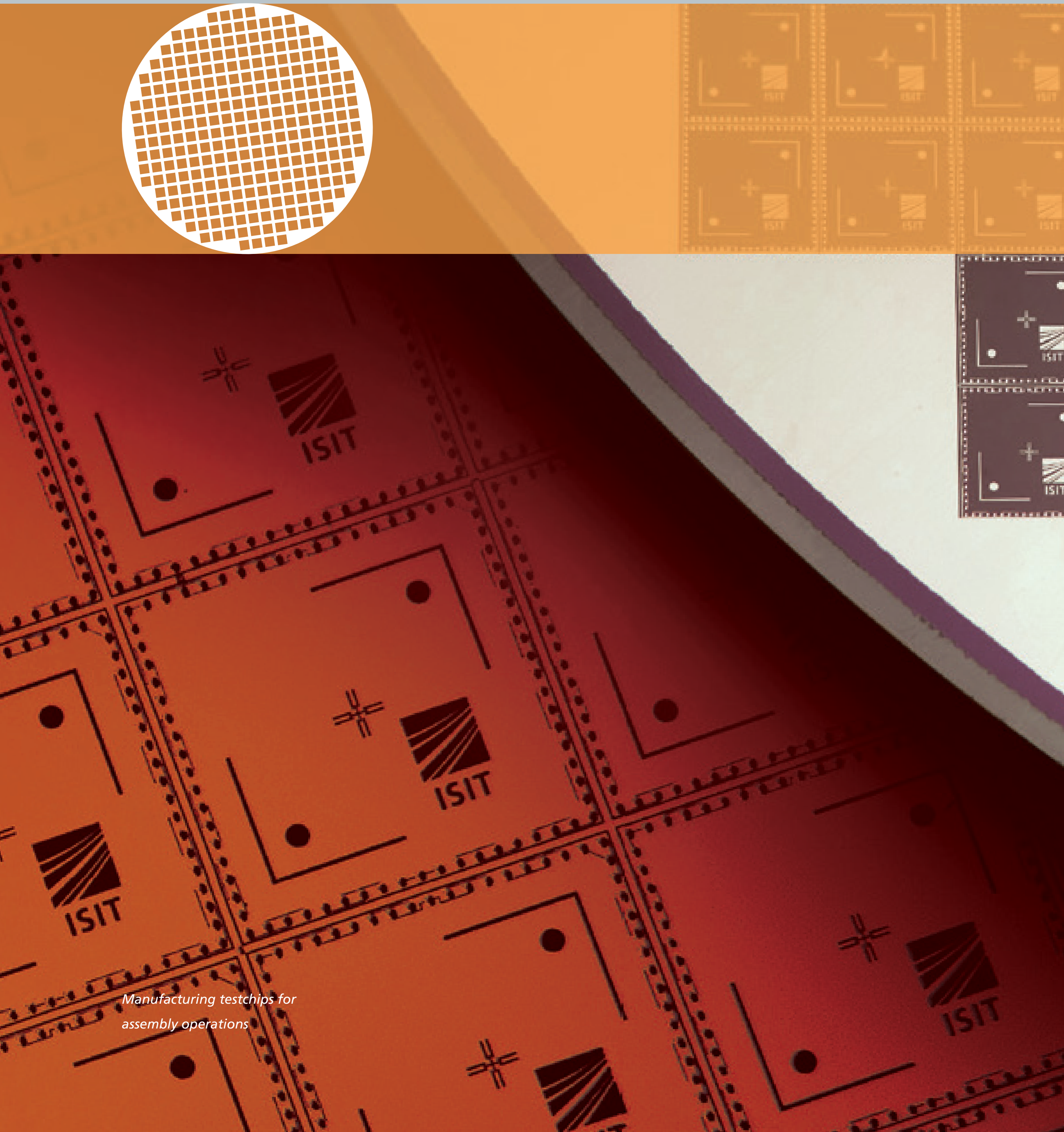
- Complete laboratory line for manufacturing format-flexible lithium accumulators
- Professional electrochemical and physical instrumentation for short-term and long-term characterization of components and cells
- Coating line for roll to roll processes

What we Offer

At Fraunhofer ISIT we offer the complete development chain for tailor made lithium ion batteries. That includes process development with upscaling towards industrial series production, prototyping and small volume manufacturing, qualifying and characterization of cells according to customers' requirements, failure and defect analysis, optimization and/or development of analytical methods, consulting services and technical studies as well as workshops and trainings.

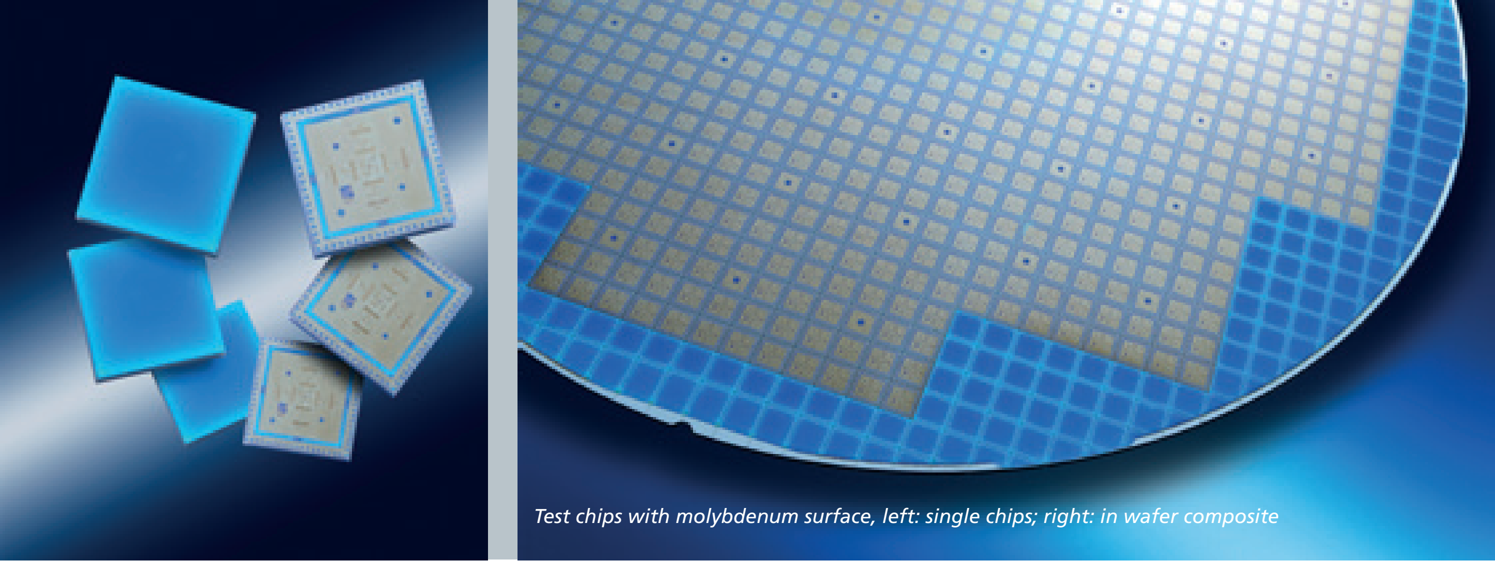
Author: Andreas Würsig

Figure 1: Lithium polymer cells for electric automotive application in fixation/cooling images of a battery module



Manufacturing testchips for assembly operations

MICRO MANUFACTURING PROCESSES



Test chips with molybdenum surface, left: single chips; right: in wafer composite

This business unit focuses on the processes, procedures, and services that constitute essential prerequisites for research and development in the Business Unit MEMS Applications on the one hand and, on the other hand, also services offered by ISIT directly in the market.

Important offerings at ISIT are wafer-level packaging (WLP) and various individual processes at the wafer level. Here the focus is on the packaging of microsystems on the wafer, but also the further processing of pre-structured wafers and the development of problem-specific technology solutions at the individual process level. The wafer technologies that are developed make it a functional part of a microsystem. Outstanding successes were achieved in the vacuum capping of MEMS sensors by means of eutectic wafer bonding. The technology basis at ISIT is excellent: Front-end processes of the Business Unit Power Electronics and the own back-end clean room line with equipment for MEMS-specific manufacturing processes can be used. The lithographic capabilities include a wide-field stepper, backside mask aligner, spray coating and spin coating, and thick resist processing. CVD, PVD, ALD and special tools for thin films are available. The wet processing area comprises anisotropic etching of Si, automated tools for metal etching, and electroplating. In case of dry etching, equipment for DRIE of Si and RIE of oxidic compounds is available. MEMS release etching can be performed using HF and XeF_2 gas phase etching or wet etching.
A specific focus is given to hermetic wafer level packaging of MEMS using metallic, anodic or glass frit wafer bonding technology. Wafer grinding and temporary wafer bonding are key process steps for thin wafer and 3D integrated products. In addition to the individual processes, Fraunhofer ISIT has established a number of qualified technology platforms. ISIT can also offer the developed components and systems to customers as prototypes or in small series from pilot production. Not only does this require proving that certain manufacturing steps and functional principles are feasible in principle, for example using demonstrators, but also taking all development steps to series readiness – an effort that must not be underestimated. High volume series production can be supported in particular through cooperation with the local company X-FAB MEMS Foundry Itzehoe GmbH, so that the industrial production of larger quantities is also possible in many cases.

BUSINESS UNIT MICRO MANUFACTURING PROCESSES

After all, Fraunhofer ISIT offers a number of services at the module level to internal and external customers as module services. In assembly and interconnection technology, ISIT specializes in the implementation of innovative processes and technologies in direct cooperation with manufacturers of assemblies, equipment, and materials. The automatic assembly of ultra-thin chips on flexible PCBs has already been tested successfully several years ago. ISIT has all basic technologies for the automated or manual handling of microchips and MEMS as well as their electrical contacting using wire bonding and flip-chip technologies. For power electronics assemblies with improved power cycle performance, ISIT has highly developed thick wire/ribbon bonding technology, both for aluminum and for copper bonding material.

ISIT has 20 years of experience with the assessment of quality, reliability, and robustness. Focal points are on the assessment of manufacturing quality, reliability testing, lifetime prediction and failure analysis, and the development of electronics as well as assembly and interconnect concepts, from the chip to the system. Beyond that, ISIT evaluates the aging behavior of assembly and interconnect techniques like chip-on-chip, chip-on-system, chip-on-board, and chip-on-polymer as well as bonding and soldering connections. The scientists create prognostics by means of model calculations, analyses under different environmental conditions, and accelerated aging tests.
They also conduct extensive assessments of failure analyses in the prognostics.

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WAFER LEVEL INTEGRATION OF SILICON LENSES FOR IR HEAT DETECTORS

All surfaces in our surrounding radiate heat as an electro-magnetic wave – similar to light, but invisible to our eyes. The ability to sense and quantify the radiation opens up a vast field of application scenarios such as person detection, monitoring medical processes and measuring heat loss in buildings and equipment.

However, a real business case only exists if cost, size and performance of a sensing system fit for the targeted application. Determining the sweet spot for a particular market thus involves thorough consideration of all aspects on the system level.

Thermal (IR) sensors can be fabricated from thermocouples, pyroelectric materials, microbolometers, photodiodes or phototransistors. To improve the sensitivity of the sensors and to shape the field of view of a detector system, IR-sensors are usually manufactured with an optical system that focuses the radiation. Depending on the type of sensor, a single lens or a combination of multiple lenses is needed. Since the IR sensors are already manufactured by microsystems technology, it is desirable to integrate lenses already on the wafer level when building the hermetically sealed IR sensor housing, as shown in figure 1.

In contrast to optical elements for the visible spectrum, lenses for long-wavelength IR applications cannot be made of glass. Except for pyroelectric motion sensors using polymer lenses, more expensive materials like Silicon (Si), Germanium (Ge) or Zinc Selenide (ZnSe) are necessary.

Although the optical properties of Ge or ZnSe are superior, Si has sufficient transmission for thin lenses and is widely available as a standard material in the microelectronics industry. With its high refractive index, only slightly curved surfaces are needed to obtain short focal lengths.

For non-imaging applications, i.e. where light just needs to be concentrated, lenses can either be manufactured as Fresnel lens or as convex shaped spherical lens. Both types can be produced only laboriously with standard Si technology. However, for a small F number, the Fresnel lens would rather generate stray light than concentrate incoming radiation on the detector element. Additionally, it is not sufficient to just

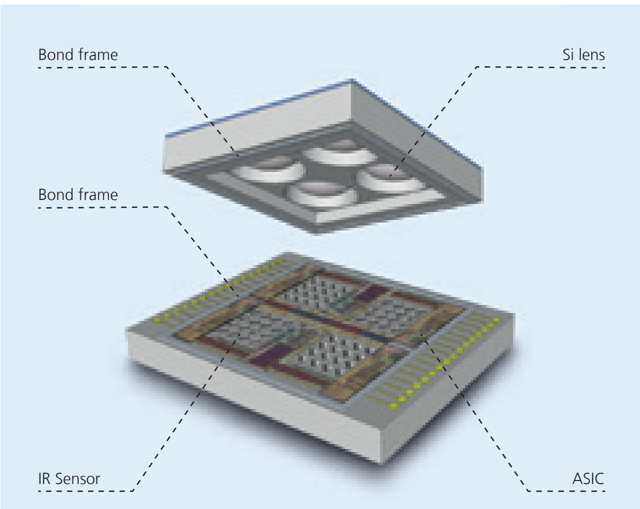


Figure 1: A typical set-up of wafer level packaged IR sensor, read-out circuit and lens as part of a hermetically tight vacuum package

produce a lens - obtaining a precise spherical shape with defined radius of curvature with good uniformity across the wafer is challenging and expensive equipment would be needed for a 100% optical test coverage.

As part of the BMBF PENTA project MIRS ("Miniaturisierte IR-basierte Sensorsysteme", FKZ 16ES0630K), ISIT has been developing an innovative process to embed refractive spherical lenses in wafer level packages. Using the exact curvature of spherical preforms that are subsequently grinded to form a plano-convex lens, the approach promises excellent optical properties for IR spot detectors and eliminates the need for optical measurements in manufacturing. The project follows up on achievements from the BMBF-funded project „Waferlevel 3D-Integration of IR Sensor Technologies" (WIN-IT, FKZ 13N12626), where modular and versatile technologies were developed to reduce the cost of IR detector systems.

Technology

Figure 2 illustrates the detailed process flow of the unique Fraunhofer ISIT approach. The new production process for Si lens arrays is based on extensive knowledge of glass forming processes in our institute that have been applied to manufacture various optical elements in the past. In a first step, holes are etched into a Si wafer by a deep reactive ion etch process (DRIE). A 200 µm glass wafer is bonded to the Si wafer, which

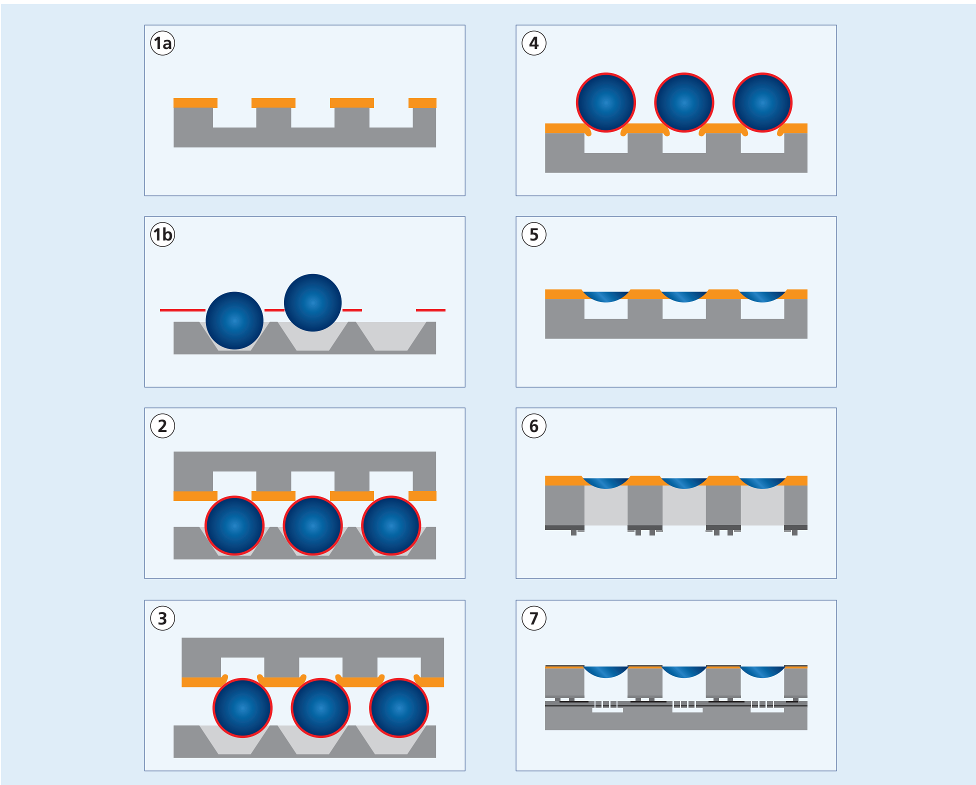
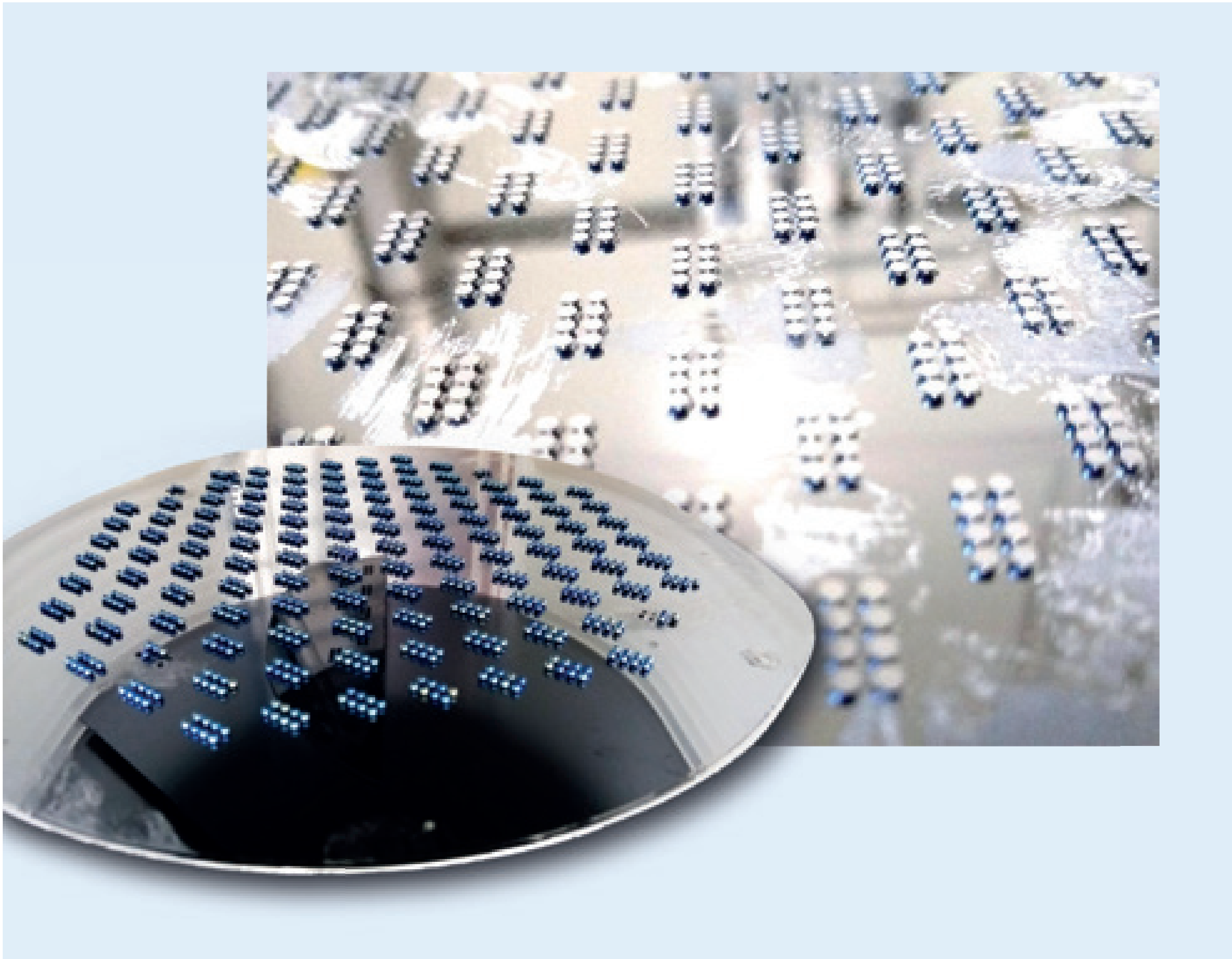


Figure 2: Process flow to integrate Si lenses on the wafer level

Figure 3: After the tempering process, the silicon spheres are firmly connected to the silicon wafer by a glass layer (left). In the grinding process they are successively ground off - here (right) the wafer was removed for testing in the middle of the grinding process



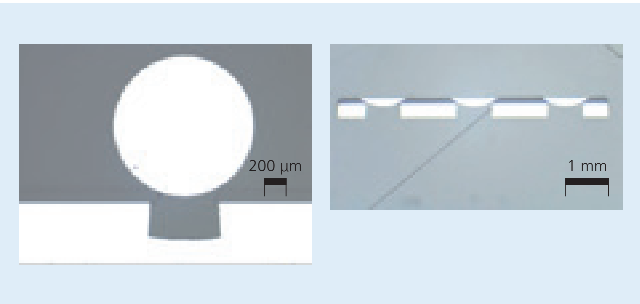


Figure 4: Cross sections (left) of the Si sphere after bonding to the structured glass / Si wafer and after grinding down the sphere to give a plano-convex form (right)

will become the optical cap of the final wafer-level package. In the next step, the glass is structured and opened in the area where Si lenses will be formed (see figure 2, 1a). A second wafer serves as a carrier for Si spheres and contains cavities in alignment with the holes in the first wafer (see figure 3). Si spheres with a selected radius are efficiently placed in these cavities by a balling process that was initially developed for attaching thousands of solder spheres on a wafer at once (see figure 2, 1b). The first wafer is then positioned above the Si spheres in the carrier wafer. A firm assembly is obtained by heating the wafer pair above the glass transition temperature while applying a uniform force. The glass adapts to the spherical surface (2), creating a strong bond between the cap wafer and the Si sphere (3).

After cooling down to room temperature the top wafer with firmly attached Si-spheres is separated from the carrier wafer (4), which can be reused several times. In the next step, the Si spheres are ground down to give a plano-convex lens shape, followed by chemical mechanical polishing to produce a planar surface of high optical quality (5). Once the lenses are formed, the next steps are to prepare the wafer for bonding by adding further elements, e.g. sealing frames, apertures, optical coatings (6). In the next step, Si is opened from the back side by DRIE to create an optical path for the lens (6). In principle, the fabrication process is compatible with glass frit or metallic seal bonding (7).

Outlook

After successful lens integration, the optical performance is now being tested. In a next step, the process will be implemented on functional CMOS sensor wafers from project partner Melexis to obtain project demonstrators. Taking the process to mass production, the main advantages of wafer level optics and in particular the Si sphere approach are that integration and alignment level are executed for several thousand systems at once on the wafer. Si spheres can be pre-selected to match the focal length requirement, promising high yield without elaborate measuring techniques at the end of the process line. Although certain limitations with respect to the pitch and the availability of intermediate sphere sizes exist, a clever design (e.g. focal length adjustment, placement of IR pixels etc.) allows to reach a commercially very relevant spot on the IR detector market.

Authors: Amit Kulkarni
Norman Laske

DEVELOPMENT OF SKILLS AND TOOLS FOR MICRO OPTO-ELECTRICAL INTEGRATION ON WAFER LEVEL

Introduction

New devices for a digital lifestyle like augmented reality (AR) glasses may find their widespread use only if consumer relevant pricing can be achieved. Low cost RGB-light sources are a key element for AR assembly productivity for these micro opto-electrical RGB-light sources and a further reduction in their package dimensions. To build miniature RGB-light sources on structured silicon wafers, a future process infrastructure based on our existing high-volume capable optical packaging platform is in development. This platform provides an optical bench with integrated heat spreader and emission windows enabling miniature hermetic housing for laser diode assemblies on 8″ wafers.

The challenge in the production of small form factor RGB-laser light engines is the hermetic optical packaging. The package form factor should enable a straight-forward integration into a projection system with an overall size that matches typical glasses frames. Light weight, ultra-low power consumption and ruggedness are further demands. Wafer Level Packaging (WLP) as a new concept realizes assemblies with good thermal properties, high optical precision and low inductance for ultra-high speed laser emission control. The possible high band-width will be particularly important for 2k to 8k video resolution at more than 50 images per second. The beam characteristics of the light engine may be customized to the projection system requirements.

Motivation and concept

A miniaturized hermetic laser diode package can be realized by a WLP approach (see figure 1). A transparent glass cap with an integrated vertical window protects especially the blue and green laser against early failure (see figure 2). Hydrocarbons have been identified to be a root cause of laser diode degradation.
Our hermetic packaging concept relies on joining materials selected for low hydrocarbon outgassing within the sealed housing.
Specific filler gas compositions may be enclosed within the cavity to further improve the environmental conditions for robust laser performance. The lateral emission enables the beam shaping by low cost optics placed outside of the hermetic laser package area. To further reduce the efforts for lens mounting, a hybrid FAC/SAC (fast/slow axis collimation) lens is in planning for second generation light engines (see figure 3) that will also help to reduce the package width.

The choice of glass as a capping material is based on its low permeability for water and gases and by the high optical transparency. The good optical quality of the emission window with respect to roughness and flatness is achieved by fusing two glasses with different softening points.

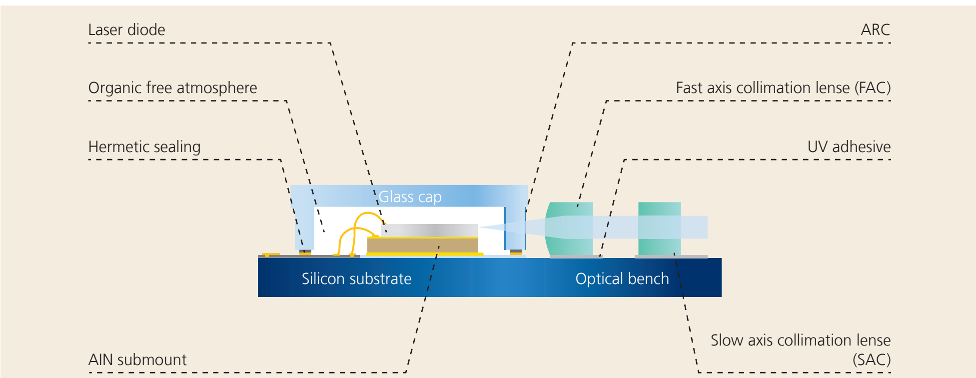


Figure 1: Schematic cross section of a miniaturized WLP laser module with an optical bench

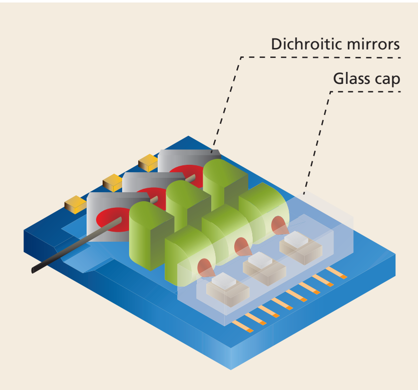


Figure 2: Schematic overview of a first generation multi-color construction of a miniaturized laser module with lateral emission window

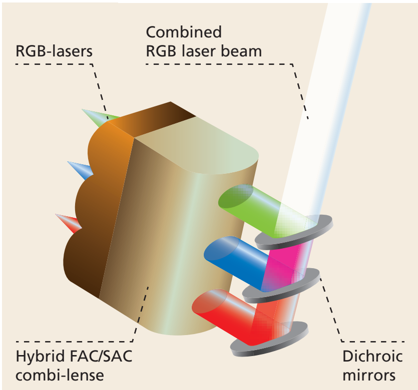


Figure 3: ZEMAX simulation of a hybrid lens design for second generation multi-color laser light engines

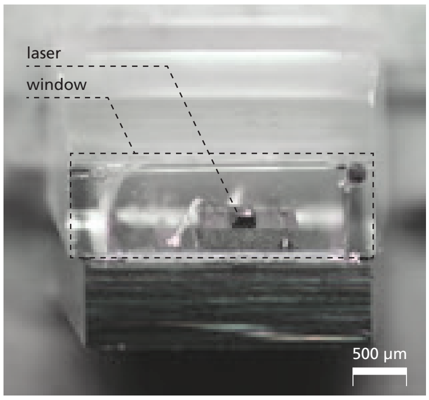


Figure 4: Front view through the emission window on a packaged laser diode

First packaged laser diodes with glass cap with vertical emission window

First simplified demonstrators were built on a silicon wafer with AuSn metallized solder pads and metal seal frames to prove the feasibility. Eutectic AuSn bonding is a joining technology widely used in opto-electronic packaging. While contact heating for first demonstrator assemblies was used, the aim is the development of in-situ laser soldering technologies for both the submount and the laser diode soldering. A sample with metallic seal bonded glass cap is shown in figure 4.

Assembly concept and infrastructure

The demand for a miniaturized multi-color laser engine requires further improvements in assembly technologies. An investment into a new ultra-precision assembly machine (see figure 5) as part of the "Forschungsfabrik Mikroelektronik Deutschland" is going on.

Considering a number of possible joining techniques, in-situ laser soldering with direct heating of selected mounting positions to reduce the heat spreading is preferred (see figure 6). This will reduce thermal effects on neighboring metallizations and mounted components, prevent premature alloying and increase the eutectic soldering throughput.

Most of the assembly job should to performed in a passive alignment strategy, finalizing the assembly with only a limited number of actively aligned components. This will balance the demand for throughput with the requirement to achieve well-defined beam properties. Experience needs to be gained

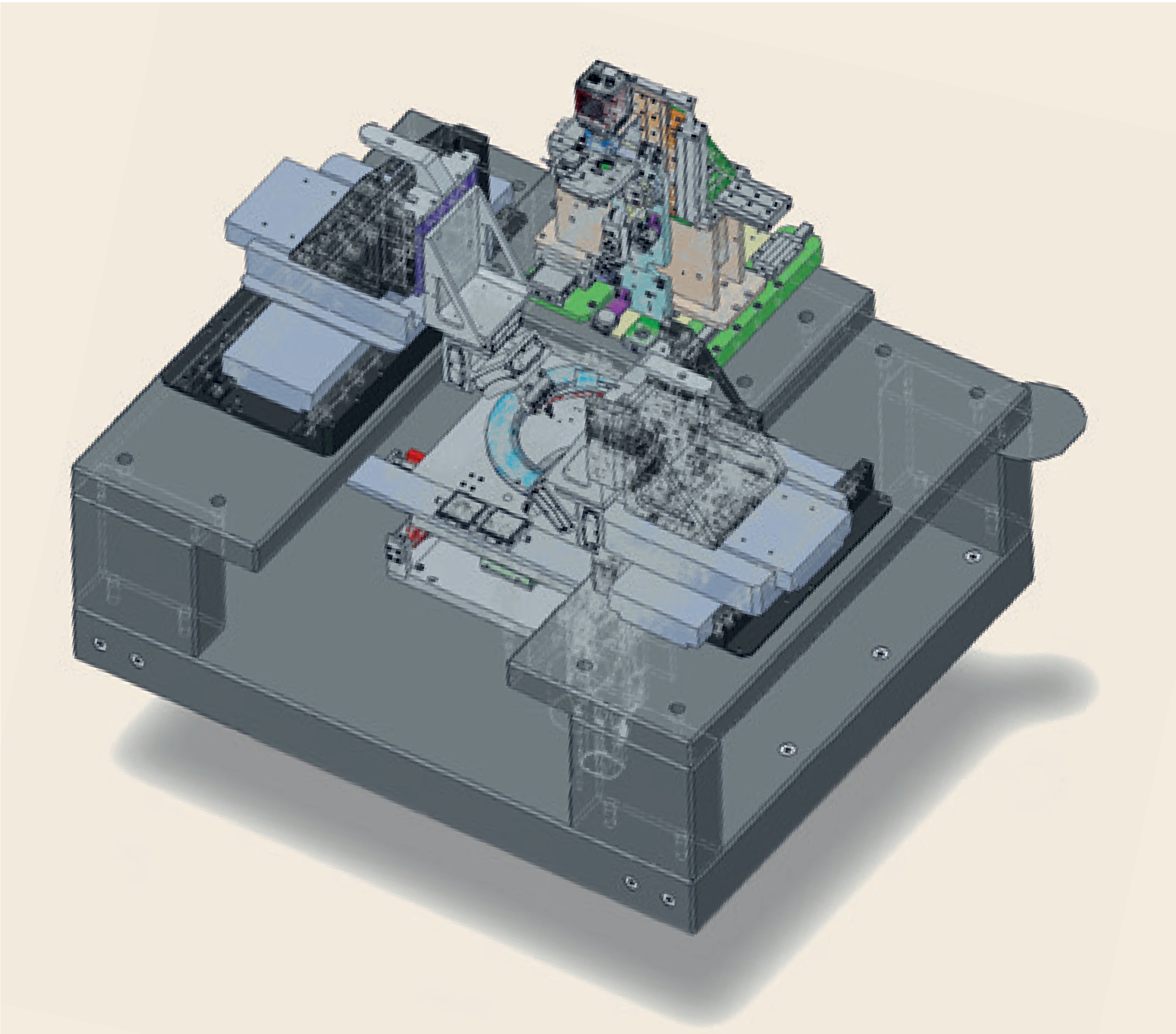


Figure 5: CAD construction overview on functional modules in the design process of a new ultra-precision assembly station with integrated in-situ laser soldering and active alignment functionality

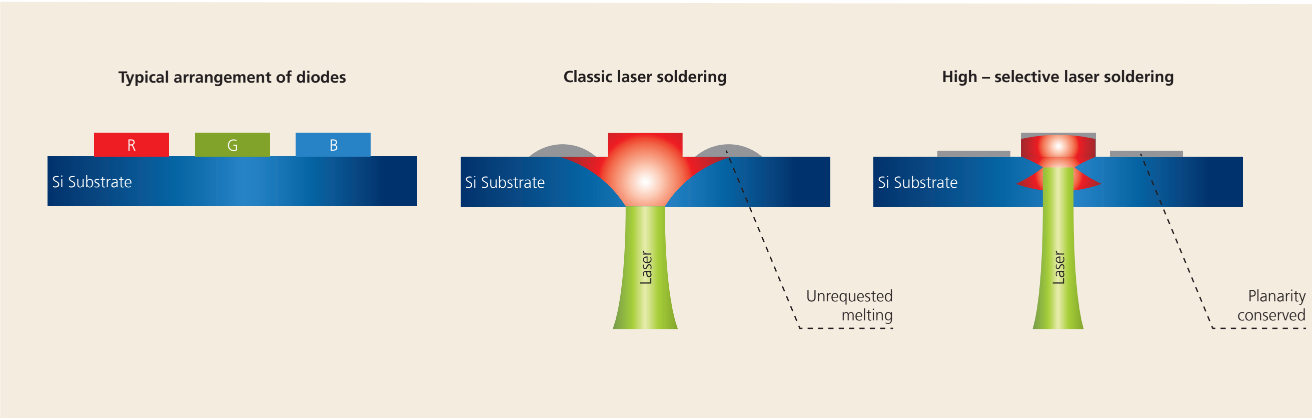


Figure 6: Concept of in-situ laser soldering with direct heat transfer to the soldering pad of a laser diode to further reduce the placement pitch by reduced heat spreading

which optical components have important influence on the optical performance and therefore define the yield.

The machine platform, built by ficonTEC Service GmbH, incorporates a beam characterization unit to allow active alignment jobs. The machine is in the production process right now and will be available for research activities in late 2019.

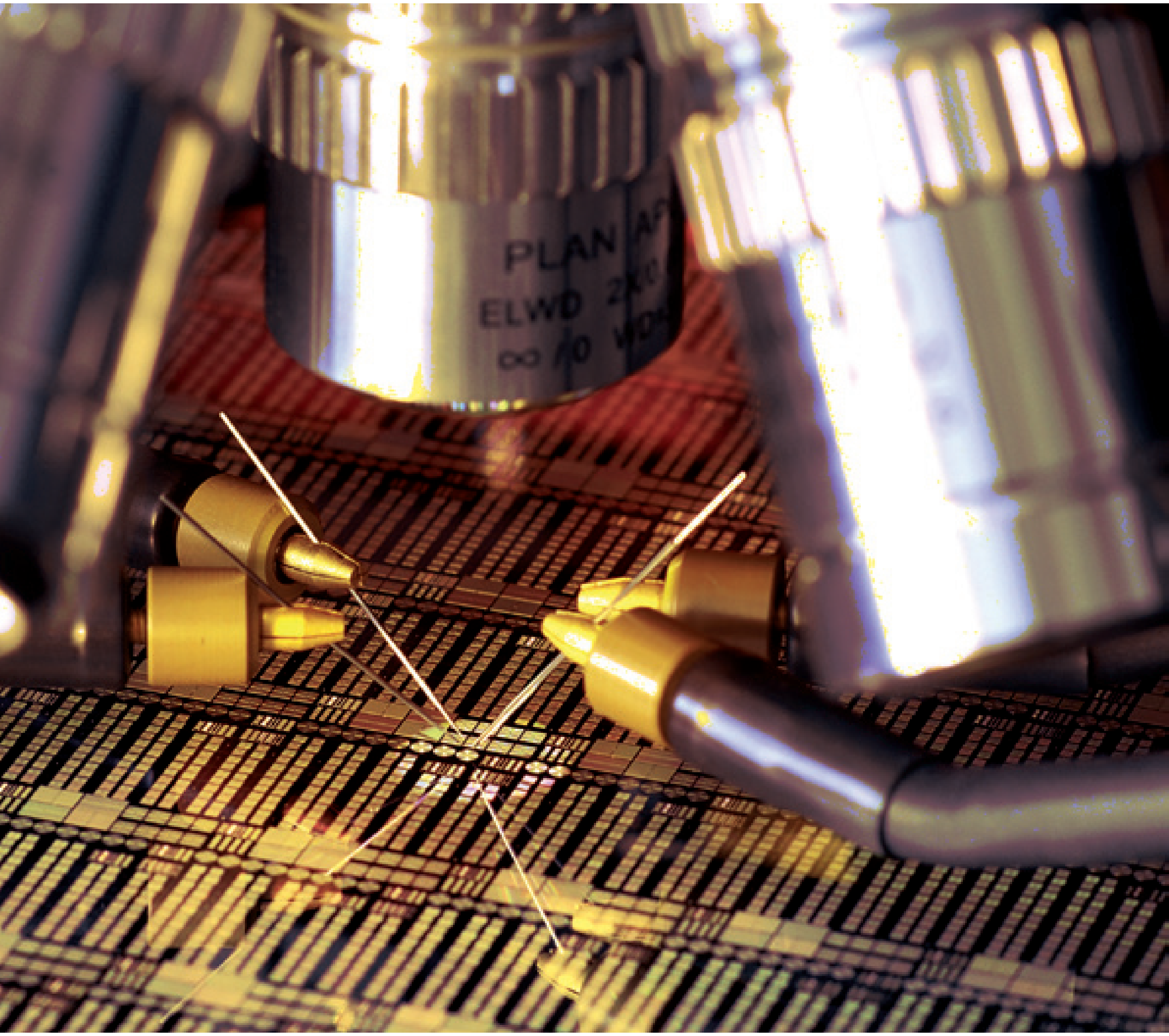
Conclusion and outlook

The new hermetic glass-silicon packaging platform enables miniature laser packages. Going from a single laser die assembly to a full optical multi-color system is a challenge in a number of technological topics. The actual work is focused on the definition of optical elements based on ZEMAX simulation and purchasing of these optical components.

The development of a low temperature sealing technique for hermetic glass cap sealing that would be applicable to our first generation light engine concept is planned. In future, we will integrate vertical vias in the substrate wafer to obtain SMD-compatible packages.

Author: Saskia Schröder

Figure 1: Wafer measurement



QUALITY AND RELIABILITY OF COMPONENTS, MICRO SYSTEMS, MODULES, PRINTED CIRCUIT BOARD ASSEMBLIES, ELECTRONIC SYSTEMS

Advanced failure analysis is the foundation of innovation, speed, quality, reliability and guaranteed lifetime function of electronic components and systems. The „Module Services“ working group deals with testing, assessment, failure and damage analysis as well as quality and reliability assessment of components, micro systems, modules and assemblies of electronics and power electronics. It provides consultancy during electronics development, including e.g. layout, assembly and production technology by experts.

Quality evaluation and reliability assessment is done by several means of analysis methods, non-destructive and destructive. The following is a list of the different analytical methods available at Fraunhofer ISIT for:

- Product Quality Evaluation
- Failure Analysis and material specific evaluation of structure
- Reliability Testing and Lifetime Prediction
- Development and Optimization of Electronics and Assembly Concepts

Product Quality Evaluation

- Non Destructive Analysis Methods

- Electrical characterization at wafer and module level (e.g. by automated wafer probing) for verification of characteristic data sheet specifications such as e.g. leakage current, dielectric withstanding voltage, dynamic behavior
- Laser vibrometry (e.g. for MEMS oscillation amplitude measurement)
- Layer thickness and optical parameter (n, k) measurement by monochromatic ellipsometry
- Determination of the switching characteristics
- High-resolution lock-in thermography
- Thermal measurements (for example by means of IR thermography) such as heat conductivity, static and dynamic thermal resistance (Rth and Zth from mW ... kW)
- Heating behavior and transient heat distribution (thermal impedance)
- Static and dynamic measurements under environmental conditions
- Combined and automated tests (electrical-thermal-mechanical)
- Evaluation of electronic assemblies according IPC-A-610 and other standards e.g. DIN, ISO, JEDEC, AEC-Q100 etc.
- Evaluation of PCBs according IPC-A-600, IPC-6012 etc.
- Optical inspection: Micro- and macro photography, digital microscopy
- surface profile analysis (confocal laser profilometry, white light interferometry)
- X-ray inspection: 2D radiography, digital computer tomography (CT)
- Thermography
- Infrared spectroscopy
- X-ray fluorescence analysis (coating thickness measurement, RoHS conformity test)

- Destructive Analysis Methods

- Metallographic analysis / cross section polishing
- Focused Ion Beam (FIB)
- Selective metal etching
- Package opening
- Solder heat resistance
- Process and production capability, e.g. Moisture Sensitivity Level (MSL)
- Scanning electron microscopy (SEM)
- Atomic force microscopy (AFM)
- Material analysis by energy dispersive X-ray spectroscopy (EDX)
- Ionography
- Wetting balance test

- Structure and Material Analysis

- Cracks (after aging)
- Damages after thermal overload
- De-alloying effects

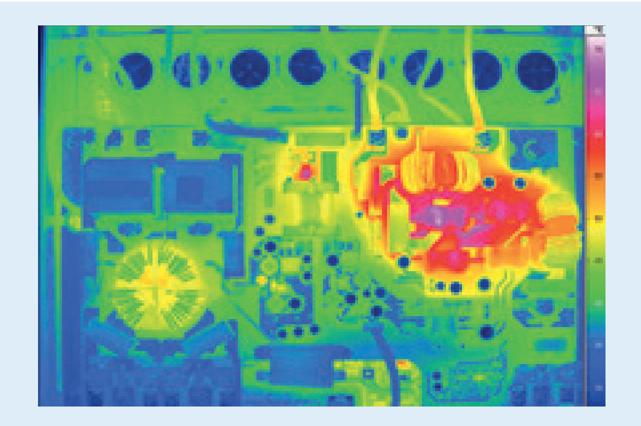


Figure 2: Heat image of a defect coil

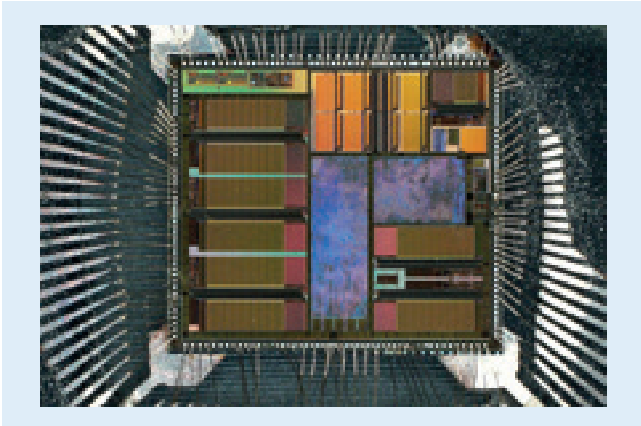


Figure 3: Wet-etch opened chip package

- Visualisation of solder texture and boundary layers
- Intermetallic phase identification
- Determination of mechanical and structural material parameter, e.g. Young's modulus, shear modulus, tear-off forces, elastic-plastic transition etc.
- Draw, shear, strain and pressure testing, also combined with thermal loads
- Shock and vibration tests for MEMS
- Pull- und shear tests (wire bonds, solder balls,…)
- Solder paste qualification

- Surface Analysis

- Contact angle measurements
- Sticking tests
- Wetting tests
- Adhesion force measurements
- Particle contamination

Failure Analysis and Material Specific Evaluation of Structures

- Analysis of thermo-mechanical behaviour
- Thermomechanical damage mechanisms at solder joints, bond wire interconnects and material compounds
- Electrical overloads
- Electrostatic discharge (ESD)
- Cracks, contamination, corrosion, dendrites, whisker, defects in conformal coating, delamination
- Dimensioning and positioning errors, parts counterfeits, 3D-SPI (solder paste inspection)
- Reconstruction of complex damage processes
- Evaluation of degradation

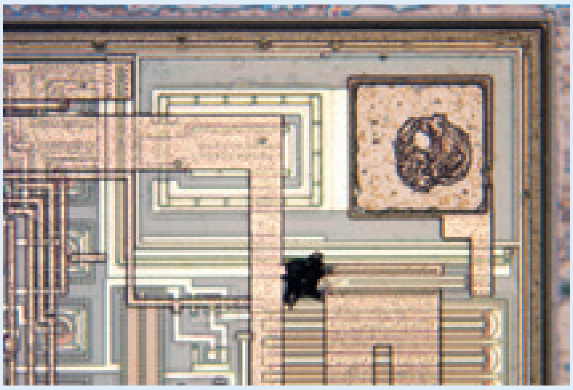


Figure 4: Electrical breakdown between conductive layers on chip

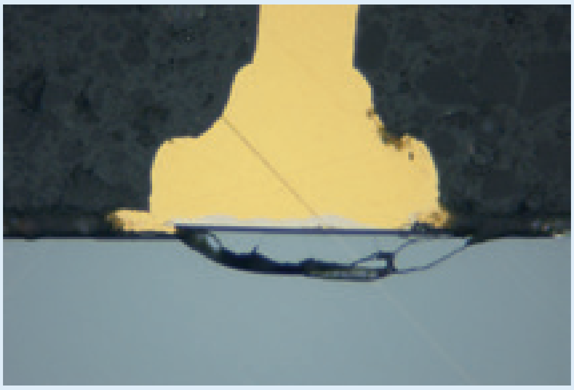


Figure 5: Crack in surface Si below a wire bond contact

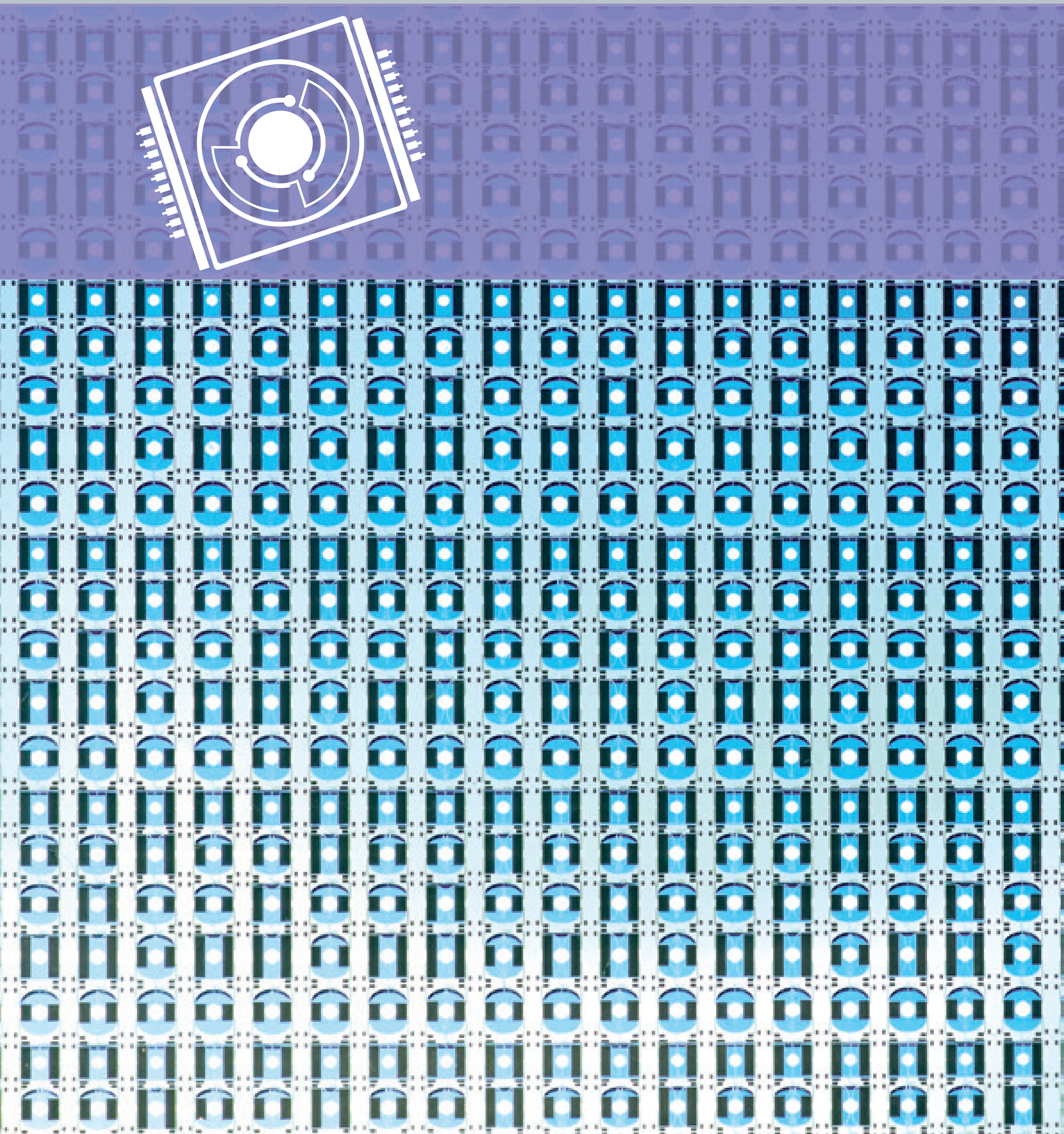
Reliability Testing and Lifetime Prediction

- Lifetime investigations with online data acquisition in customer-specific electrical and hydraulic wiring with active and passive accelerated aging
- Accelerated aging with online data logging (climate testing, thermal shock, thermal cycling, high temperature storage)
- Active power cycle test up to 2000 A (to intentionally induced component damage)
- Model calculations to the prediction of lifetime (by suited accelerated aging mechanisms) on basis of observed failure mechanisms
- Surface insulation resistance (SIR) test

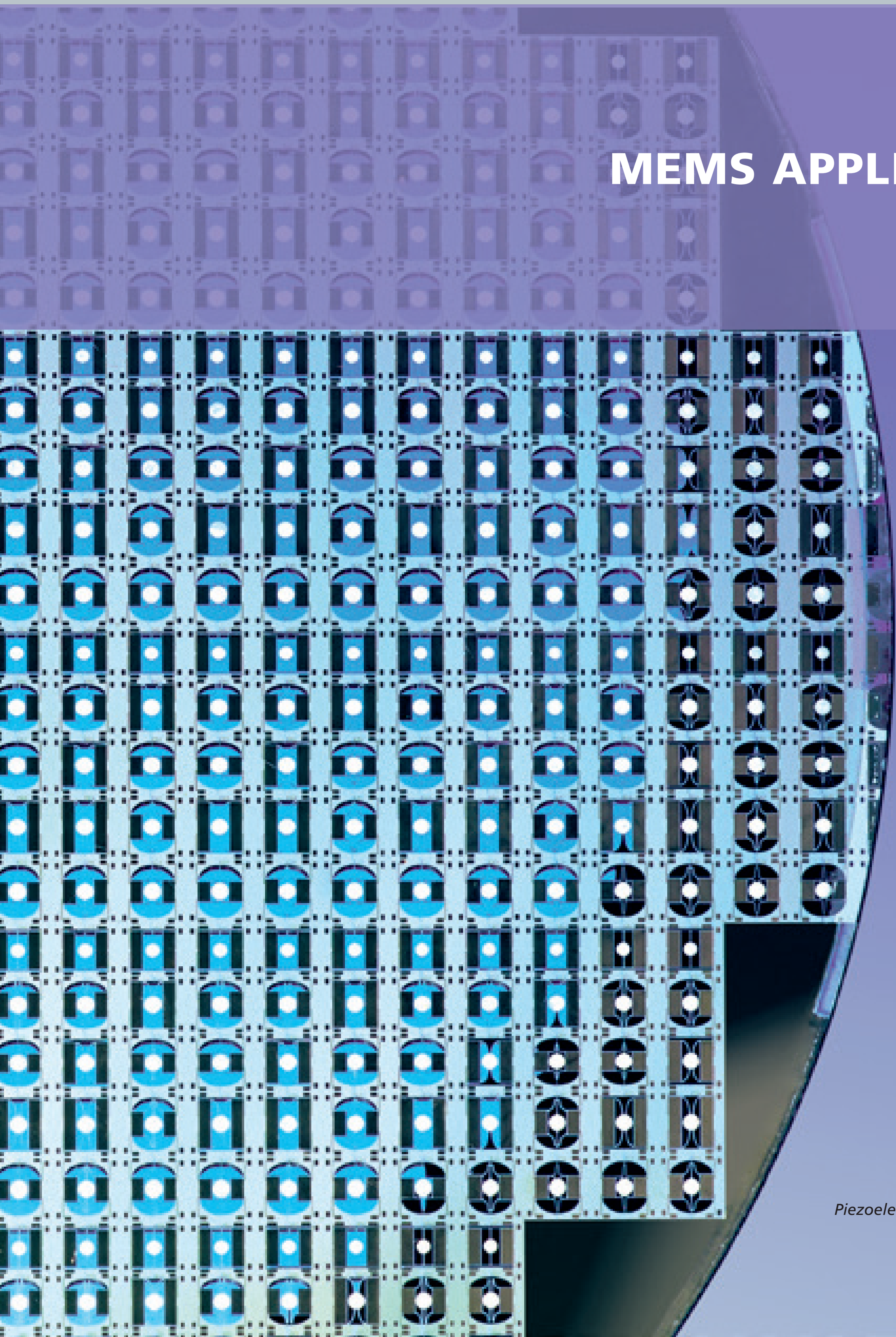
Development and Optimization of Electronics and Assembly Concepts

- Electronics and system conception (analog, digital, power electronics)
- Thermal design (simulation of the thermal management of components, modules and assemblies)
- Thermo-mechanical simulation (static, transient)
- Modelling of thermomechanical loads due to material incompatibilities (bending of laminates, creeping of solder)
- Modelling of cooling devices, e.g. geometry dimensioning of air coolers and liquid coolers
- Evaluation of the efficiency of cooling concepts
- Assessment of relevant features of manufacturing quality and reliability
- Strain measurement (CTE mismatch) for process qualification

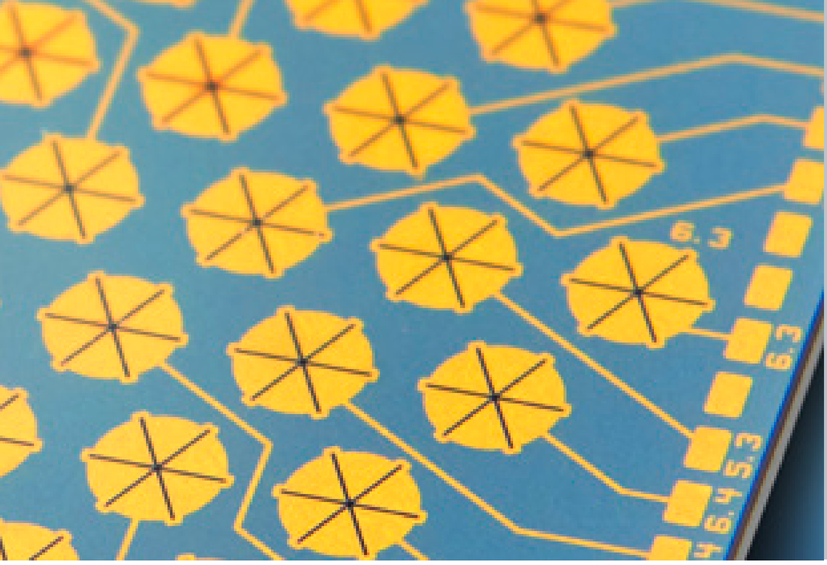
Author: Helge Schimanski



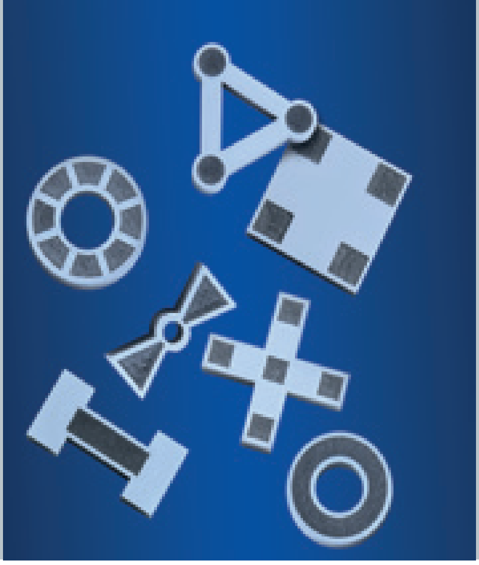
MEMS APPLICATIONS



Piezoelectrically driven MEMS mirrors



Array of ultrasound transducers

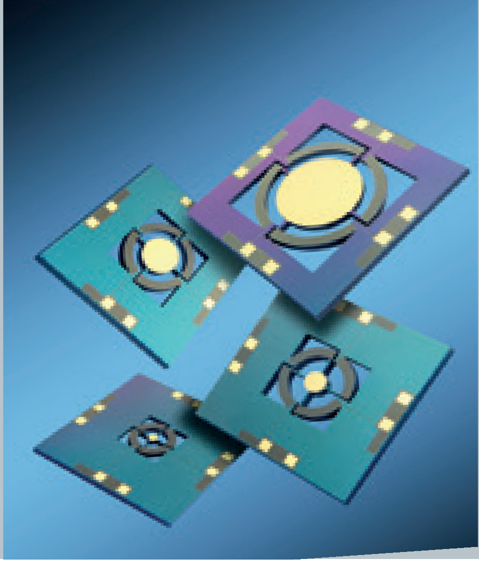


Various magnetic structures

ISIT scientists have been working on the development of micro electro mechanical systems (MEMS) for more than 30 years. In the Business Unit MEMS Applications, ISIT focuses on the design, development, and production of MEMS components and MEMS systems.

Optical microsystems are a major focus in this business unit. ISIT develops vector scanners as well as resonant MEMS scanners including control and readout electronics for various types of laser projection displays, for optical measurement and detection systems (e.g. LIDAR), for applications with high laser power in the field of material processing and generative manufacturing as well as for the use in optical telecommunications.

Based on a patented manufacturing process, ISIT is currently the world's only manufacturer of two-axis, wafer-level vacuum-encapsulated resonant MEMS scanners. Operating these scanning micromirrors in a vacuum environment offers significant advantages. Damping by the gas molecules is reduced to a minimum, enabling high-frequency scanning with unrivaled scan angles even at low electrostatic driving voltages. Hermetic encapsulation at the wafer level also results in the cost-effective and permanent protection of the scanning micromirrors against all kinds of contamination. This for example makes the steam sterilization of these MEMS scanners in an autoclave for endoscopy applications possible without causing damage.



Different types of piezoelectric micromirrors

BUSINESS UNIT MEMS APPLICATIONS

ISIT has also realized a 3D camera with a depth resolution of just a few millimeters and a detectable object distance of 2 meters on the basis of 2D MEMS scanners. Novel scanning micromirrors with apertures of up to 2 centimeters and highly reflective coatings even permit highly dynamic dual-axis laser beam deflection for CW laser outputs of up to 500 watts. In addition to capacitively driven resonant scanning micromirrors, ISIT also focuses on piezoelectrically driven vector scanners. These systems are characterized by a very high force-density combined with low energy consumption and allow quasi-static deflections of more than ±10°.

A further focal point in this business unit is acoustic microsystems. In this fast-growing field, ISIT is an international leader in research into innovative, highly miniaturized loudspeakers for applications in wearables, hearing aids, AR/VR, wireless headphones and smartphones. These MEMS loudspeakers are at least as good in acoustic quality as their conventional electrodynamic counterparts, but are significantly less expensive and can be fabricated more miniaturized. Further advantages are the high energy efficiency and the high acoustic bandwidth (20 Hz - 100 kHz) of these components. This makes ISIT's chip-level loudspeakers particularly attractive for mobile communication devices such as tablets, smartphones, headphones and hearing aids in which high acoustic quality is required while at the same time further shrinking in size and low energy consumption are targeted. Ultrasonic microsystems, e.g. for 3D distance measurements and haptic man-machine interfaces, are another research topic. Depending on the frequency range, the transducers at ISIT are usually designed as thickness-mode or membrane transducers with AlN, AlScN, or PZT as drive materials. Efficient ultrasound transducers with center frequencies of a few kHz to several hundred MHz can be realized this way.

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QUASI-STATIC MEMS MIRROR FOR VECTOR SCANNING

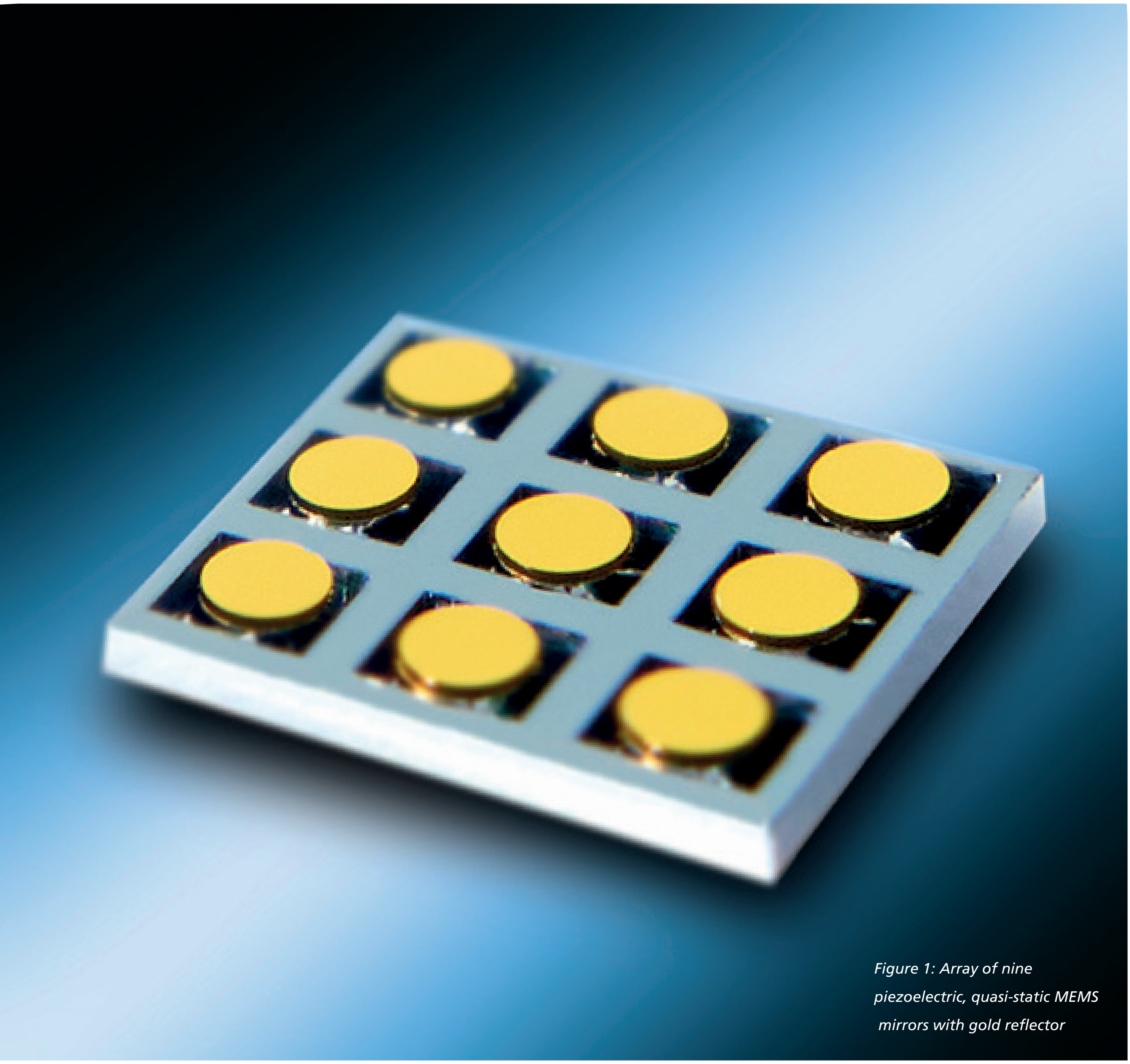


Figure 1: Array of nine piezoelectric, quasi-static MEMS mirrors with gold reflector

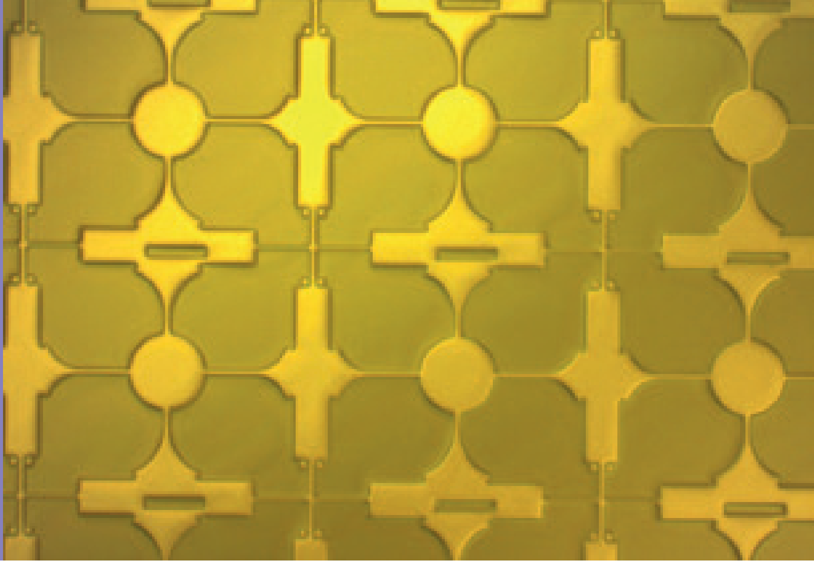


Figure 2: Microscope image of the piezoelectric actuator layer

Motivation

Scanning micromirrors based on the resonant driving mode have a long history track at ISIT. However, the non-deterministic movement in resonant operation is not suitable for all applications, in particular in the industrial field that requires perfect control of laser trajectories with arbitrary speed down to full stop ("quasi-static" positioning).

Vector scanning MEMS mirrors use actuators that directly translate a static DC voltage into an angular deflection. They have low inertia, small footprint and low power consumption. A constantly increasing market interest can be observed for a broad diversity of applications, like optical communication, material processing and LIDAR (light detection and ranging).

Current State

In a customer project, Fraunhofer ISIT demonstrated an array of efficient vector scanning MEMS mirrors (see figures 1 and 2) with 0.8 mm aperture diameter. The actuators are based on piezoelectric driving structures that are created by depositing a stack of thin films and subsequent underetching. The scanner reaches a high static mechanical deflection of up to 12.5°. Excellent linearity, great repeatability and long-term stability have been achieved by using Aluminium-Scandium-Nitride (AlScN) as a driving material. Additionally, the efficient construction and patented, "rose-leaf" shaped suspension structures (see figure 3) eliminate mechanical non-linearity and minimize pitch size. Current efforts target to build a technology platform that supports many different applications only by adapting the MEMS design.

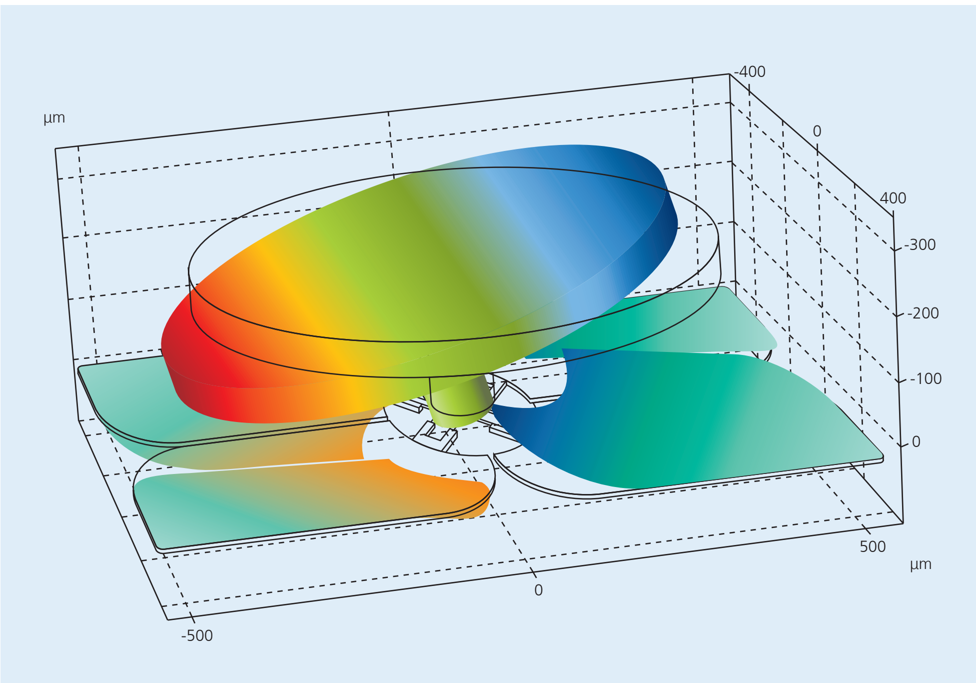


Figure 3: The patented "rose-leaf" actuator with suspension structures minimizes the pitch size and improves mechanical linearity

Next Steps

Current design efforts for quasi-static MEMS mirrors target only small aperture sizes (≤ 2 mm). However, ambitious market expectations for larger mirrors must not be ignored: Traditional options like galvanometer mirrors show stable performance, but cannot avoid a large inertia due to their high mass. Scanning speed and angles (in particular for 2D scanners) are very limited and the price cannot be reduced. More and more application designers therefore urgently wish to replace their galvanometer scanners by large quasi-static MEMS mirrors. Using conventional MEMS driving principles, however, will not show significant advantages: A trade-off always has to be made between mirror size, scanning speed and scanning angle. If a MEMS technology can deliver driving forces of one order of magnitude greater than today, the design limits could be extended. Former attempts for magnetic MEMS actuation by integrating coils on Si-wafers and utilizing external magnetic fields do not deliver sufficient performance, but Fraunhofer ISIT is working on a unique technique of integrating permanent micro-magnet structures into Silicon wafers. In this way, forces up to 10 mN are possible, which is much stronger than piezoelectric drives. Furthermore, the embedded micro-magnets can be arbitrarily shaped and placed as arrays to upscale the available driving force (see figure 4).
Besides setting up the technology platform, the current working focus for magnetic actuation lies also on developing the most efficient electronic driving unit including coils for low power consumption and accurate motion control.

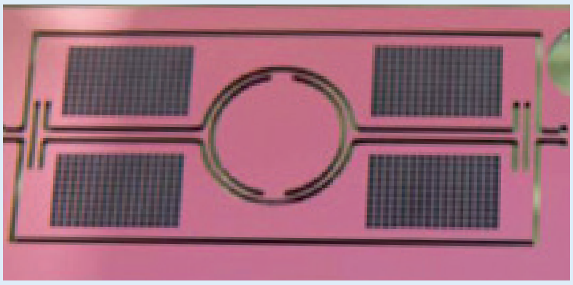
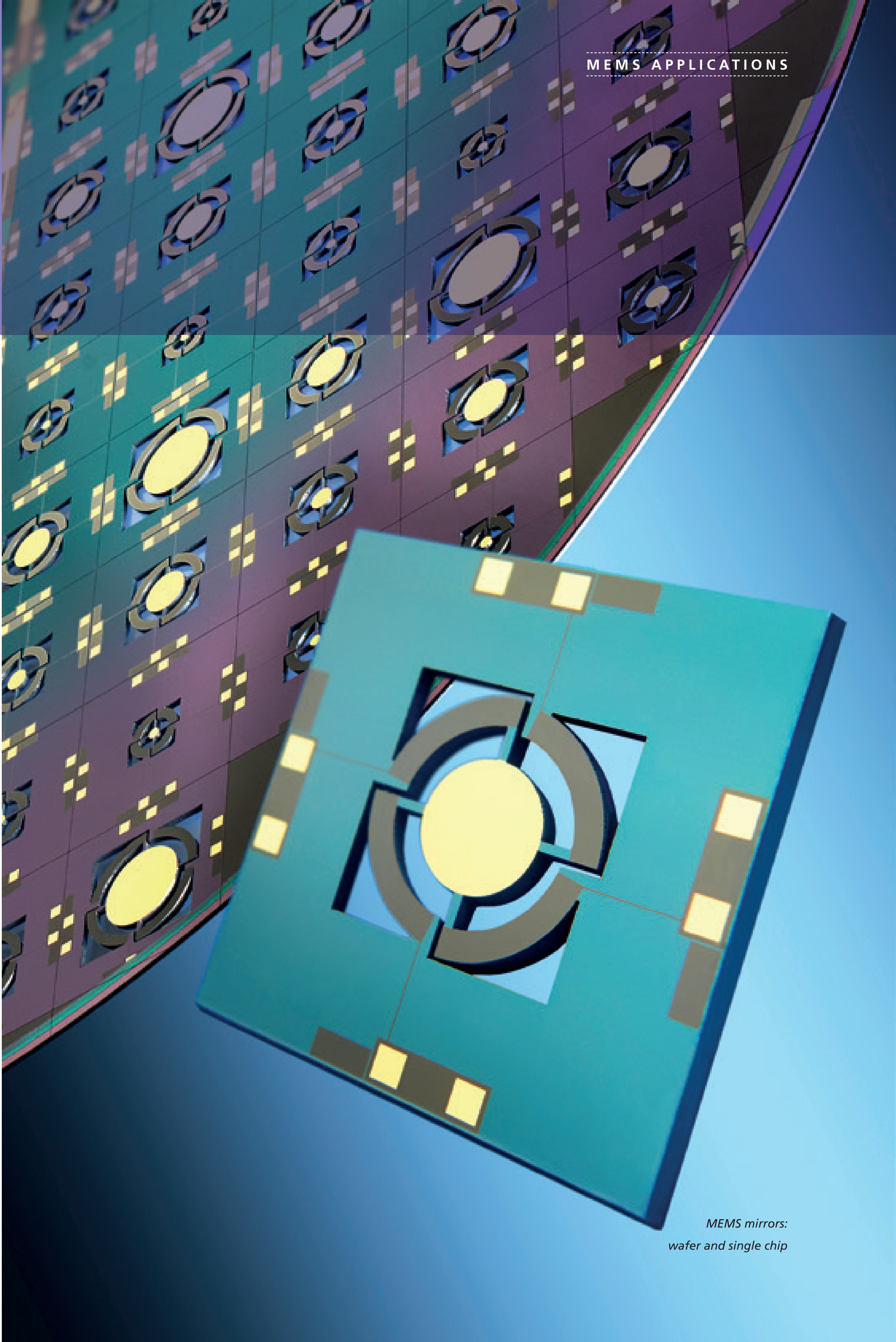


Figure 4: Quasi-static MEMS mirror actuator using four arrays of embedded permanent micro-magnets

Outlook

MEMS mirror scanners are massively entering the market. However, many - in particular industrial - applications are not yet in reach of available actuator technologies. Fraunhofer ISIT is strongly involved in developing materials and their wafer level integration as an enabler for future MEMS generations. The latest progress on piezoelectric drives and magnetic structures offers great opportunities for a broad diversity of applications requirements. ISIT's technology platforms will allow efficient customization of application specific microsystems consisting of drive units, sensing elements and controller circuits.

Author: Shanshan Gu-Stoppel



MEMS mirrors:
wafer and single chip

LIDAR CAMERA BASED ON RESONANT SCANNING MEMS MIRRORS

Motivation

Actual demands in traffic and society like autonomous driving, drones and multiple 3D object recognition tasks drive the development of small, cost-efficient LIDAR (light detection and ranging) systems. Existing 3D imaging systems based on focal plane arrays with a modulated light source suffer from a limited resolution, a relatively high energy consumption of the light source and potential interference with other systems. These limitations can be overcome by using a MEMS scanner with a directed laser beam. Current LIDAR scanning systems with electrostatic MEMS reach 40° scanning angle in both directions, while Fraunhofer ISIT's new generation of piezoelectric driven MEMS scanners can achieve extreme optical scan angles close to 180° (see figure 4), owing to the high torque delivered by the piezoelectric material.

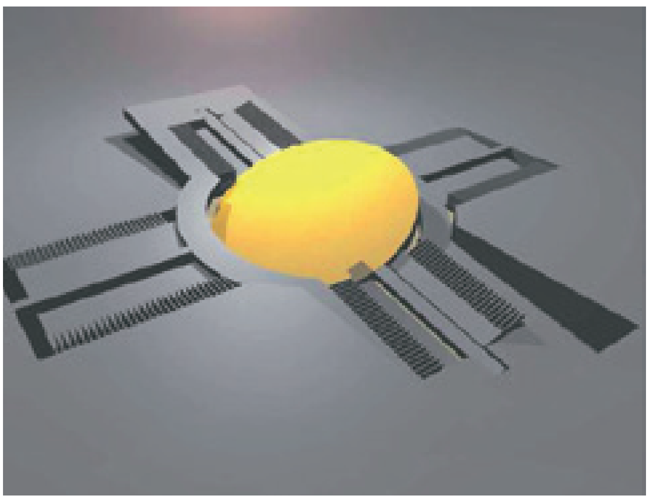
Achievments

Resonant MEMS scanners are much smaller and faster than polygon- or galvanometric scanners. They are manufactured in wafer-level processes, which is suitable for high volumes but involves a significant amount of non-recurring engineering costs. The achievable scan speed and the capability to integrate two scan axes in a very compact device are fundamental advantages of MEMS scanning mirrors over conventional galvanometric scanners. Significant effort is being spent to increase their field of view and to fulfil automotive qualification targets, especially concerning the mechanical and thermal robustness. Although resonant scanners reach much larger scanning angles than our piezo-based, quasi-static mirror drives, there are interesting application perspectives for both technologies.

Internal tests have shown that MEMS scanners are very reliable in standby as well as in working mode. A closed-loop resonant mirror drive will provide a very stable mirror oscillation. Moreover special designs for mechanical shock resistance have been developed.

Figure 1: Front view of the full LIDAR system demonstrator

Figure 2: Example of a 2D MEMS scanner design



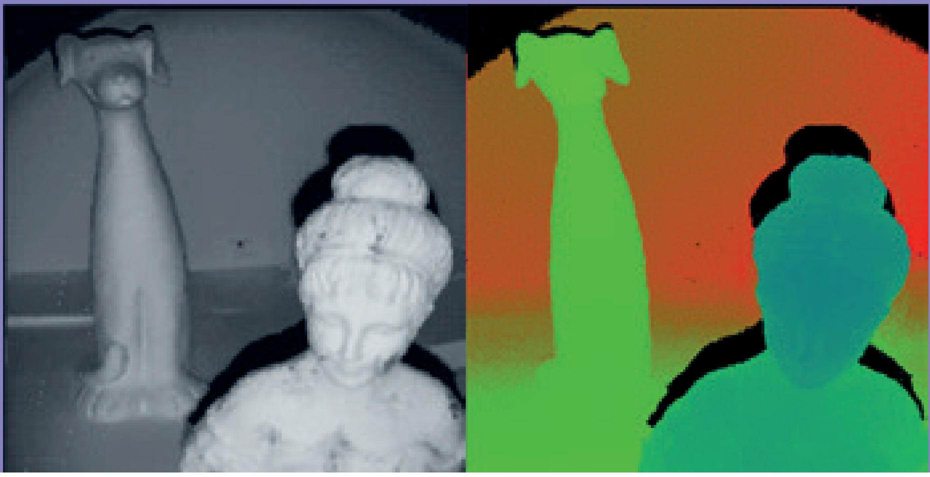


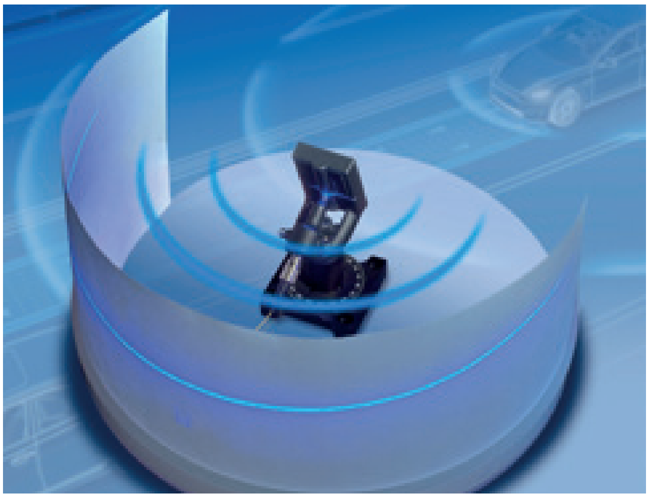
Figure 3: Different working modes of the camera. Left: Reflected light intensity, Right: Phase shift between light source and reflection

What we Offer

Fraunhofer ISIT has developed a LIDAR camera demonstration with 2D scanning resonant MEMS mirrors. The amplitude of a laser beam is modulated and the phase difference between the light source and the reflection is measured. A real-time measurement is realized by using a single pixel APD (avalanche photo diode). The light projection engine can be miniaturized to almost sugar cube size, but requires a large camera objective (see figure 1) to retrieve sufficient signal strength from the reflections.

The first demonstration - consisting of a 2D MEMS scanner, a digitally modulated laser, detection optics and the APD sensor - achieved the following specifications:

- Resolution 450 pixel x 450 pixel
- Framerate 6 fps (currently limited by the viewing software)
- Detection range 0.1 m - 8 m
- Relative depth measurement accuracy 5 mm - 10 mm
- Sample rate 80 MHz
- UDP Ethernet interface



The laser beam is directed towards the scanning mirror under an angle of 22.5°. Figure 2 shows an example of a 2D scanning MEMS mirror that will project a so-called Lissajous trajectory, which is a sinusoidal movement along two orthogonal axes. The slow horizontal axis oscillates with a frequency of 525 Hz, covering a total optical scan angle of 40°. The fast vertical axis has a resonant frequency of 16.4 kHz, also covering a scan angle of 40°. These parameters correspond to a projection area of about 1.5 m x 1.5 m in a distance of 2 m.

In order to reach such high amplitudes, the scanner is hermetically sealed in a wafer-level package under vacuum. A tilted glass lid shifts the parasitic specular window reflex out of the projection plane - this particular design was developed by Fraunhofer ISIT using a unique glass forming technology for wafer-level optics.

For demonstration, the laser illumination is in the visible range (658 nm), but near-infrared light can also be used with this scanner type. The continuous laser power of 130 mW can be modulated digitally with a maximum bandwidth of 350 MHz, at low duty cycle for the reason of eye safety. In the present setup, a modulation frequency of 75 MHz is used. The detection optics with its large aperture size (d = 60 mm) allows to capture reflected light from objects within the total optical scan angle of the 2D-MEMS scanner. By using different algorithms, either the light intensity or the phase shift of the monochromatic illumination can be visualized (see figure 3).

Author: Thomas Knieling

Figure 4: Piezoelectric driven MEMS scanner with large scan angle of 160°

ACOUSTIC SYSTEMS AND MICRO ACTUATORS

The group Acoustic Systems and Micro Actuators at Fraunhofer ISIT combines the expertise of micro actuator concepts and their fabrication with the fast developing field of MEMS acoustics. Applications range from audible acoustics for consumer applications over airborne as well as liquid-borne ultrasound up to structure-borne sound for technical applications. Acoustic MEMS devices cover both, the generation of sound (loudspeaker) as well as its detection and measurement (microphone).

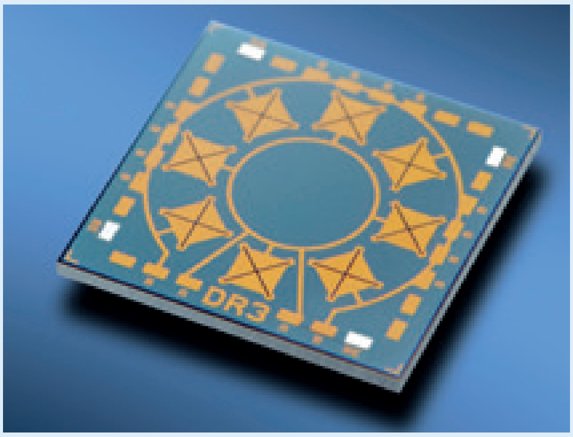


Figure 3: MEMS chip for ultrasonic application

Figure 2: MEMS microspeaker in an in-ear headphone prototype

Revolution in headphone speakers

Our reference system is a MEMS microspeaker based on piezoelectric bending actuators for use in headphone applications. With an area of only 4 mm x 4 mm the MEMS microspeaker enables sound pressure levels of more than 110 dB measured in a 2 ccm ear simulator with a flat frequency response over a broad range from 20 Hz to 20 kHz. The high energy efficiency and low distortions make it the ideal microspeaker for truly wireless high-fidelity in-ear headphones and wearables.

Wide range of technologies

To achieve the best results and tailor the systems to the target applications, we have numerous complementary technologies at our disposal. The utilized concepts include but are not limited to magnetic, electrostatic and piezoelectric interaction. The fundamental effects are implemented in a variety of geometries to be utilized for high performance micro actuators.

Specialist in piezoMEMS

A special focus with more than 10 years of experience lies in the utilization and integration of piezoelectric materials. Our piezoMEMS technology platform today comprises the functional materials lead zirconate titanate (PZT), aluminum nitride (AlN) as well as aluminum scandium nitride (AlScN). A typical implementation is the use in unimorph structures,

Variety of piezoelectric MEMS devices for acoustic applications on an 8-inch wafer

where the piezoelectric material works against a passive second layer to induce bending.

What we offer

At ISIT we offer the full development chain for acoustic MEMS and micro actuators. Starting from the concept phase we use our broad system know-how and numerical simulations to find the optimal design of the MEMS device for the application requirements together with its integration into the system. The fabrication process is developed using our 200 mm silicon technology in-house capabilities complying with industry standards, together with assembly for extensive characterization and testing of the produced prototypes. The developed process and facilities can subsequently be used for pilot fabrication or transferred to a high-volume manufacturer.

Benefits of MEMS Acoustics

- High miniaturization yielding smallest sizes
- Excellent integrability to microelectronics
- Highest energy efficiency
- High-volume, low-cost manufacturability using silicon technology

Our Service

- Expertise and IP in the field of micro actuators and MEMS acoustics
- Full development chain for MEMS devices and systems: concept, design, simulation, fabrication, assembly, characterization and testing
- Pilot fabrication of MEMS
- Partnership for future developments in the field of MEMS acoustics and micro actuators

Author: Fabian Stoppel

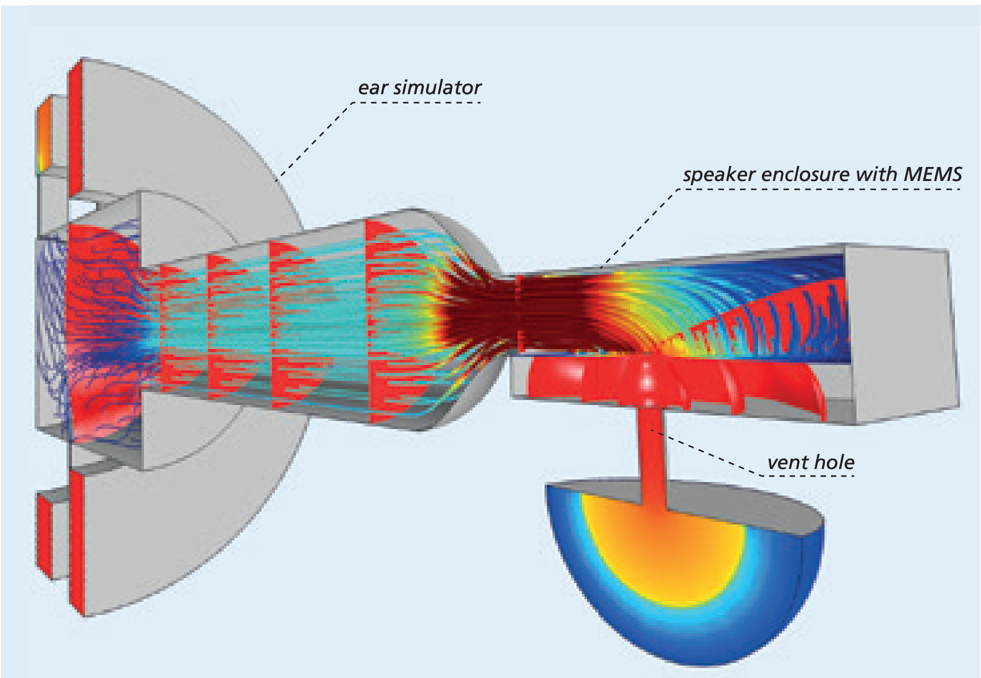
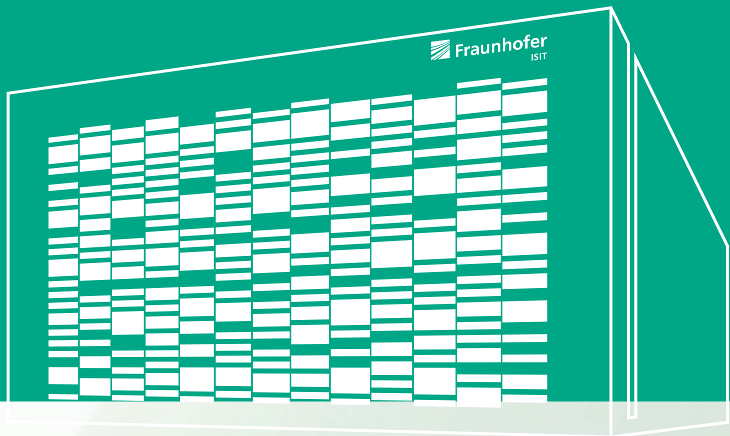
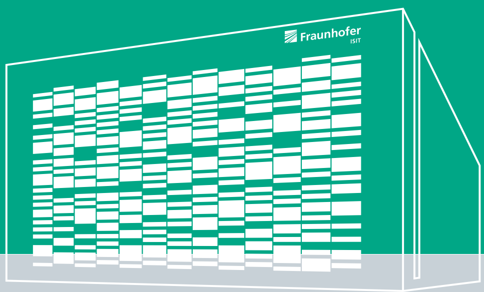


Figure 4: FEM simulation of a MEMS in-ear speaker coupled to an ear simulator



TECHNOLOGY

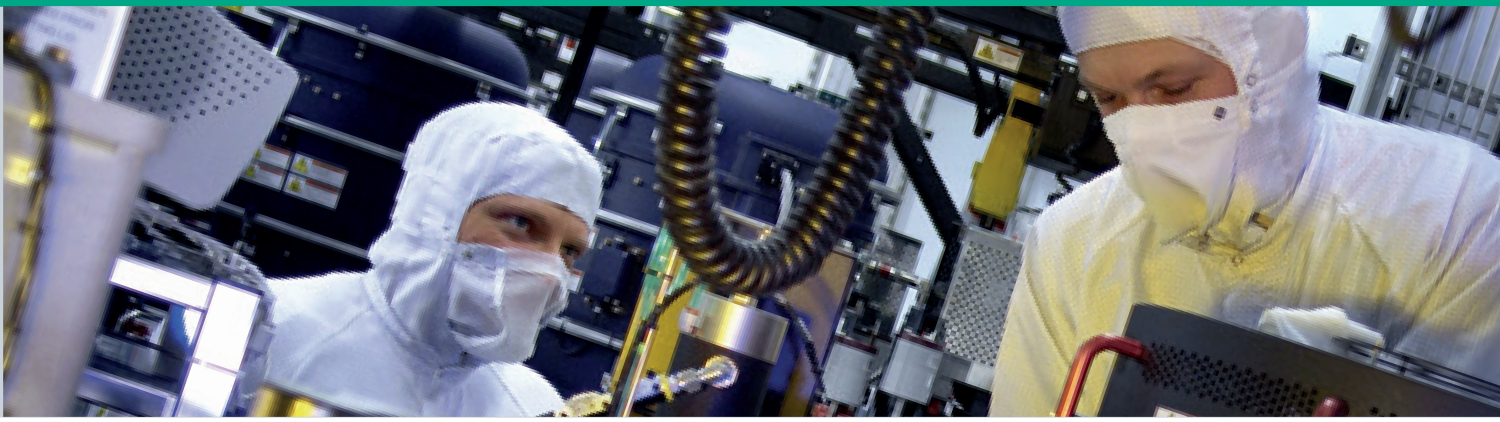


TECHNOLOGY

Fraunhofer ISIT is running a 200 mm Silicon technology line (2500 m^2) for front-end processes (MOS and PowerMOS). Specific processes for MEMS and NEMS as well as for packaging are implemented in a special and newly built cleanroom (1000 m^2). This includes wet etching, dry etching, DRIE, deposition of non-IC-compatible materials, lithography with thick-resist layers, electroplating, microshaping, and wafer bonding. Further cleanroom laboratories are set up for chemical-mechanical polishing (CMP) and post-CMP processing.
Extra laboratories covering an area of 1500 m^2 are dedicated to electrical and mechanical characterization of devices, assembly and interconnection technology, and reliability testing. Fraunhofer ISIT also operates a pilot production line for Li-polymer batteries. The institute's facilities have been certified to ISO 9001:2015.

Technology-Platforms
ISIT has a wide portfolio of qualified single process technologies available, which were combined to five specific technology process platforms. They form a kind of tool box to realize various applications.
In addition, Fraunhofer ISIT has further technology offers, e.g. for the development of lithium batteries.

Poly Silicon MEMS Technology Platform (PSM-X2)
The technology platform PSM-X2 features a low stress 10–30 µm thick polysilicon layer for the realization of mechanical active and passive MEMS structures. The use of high resolution lithography allows minimal structure dimension down to 0.5µm. An additional electrode layer beneath the active polysilicon layer is implemented. This gives the opportunity for out-of-plane signal detection or sensor stimulation. Additive functional layers enhance reliability and robustness of the MEMS devices (anti stiction, high-g shock). For the wafer scale bonding of the sensor device and the protective encapsulation a dedicated multi pressure wafer level packaging process is applied using e.g. a gold silicon eutectic process at about 400°C. The metallic bond frame induces a hermetic encapsulation of the cavity and the pressure applied during the bond process will persist. Integrated getter films allow cavity pressure levels down to 10^{-6} bar and a pressure ratio within adjacent cavities of up to 1:400. The application range of PSM-X2 platform includes e.g. inertial sensors, micro mirrors or electro-optic deflection devices. Recently, Fraunhofer ISIT has developed an innovative process technology for the manufacturing of sophisticated MEMS scanners ($^2\varepsilon$ Process), called "Dual-Layer EpiPolySilicon Process". Following the success of the well established surface micromachining technology PSM-X2 for inertial sensors, the $^2\varepsilon$ process is based on structuring two 30 microns thick epitactically grown polysilicon layers. This allows the realization of staggered finger combdrives for mirror actuation and detection and the design of suspension.



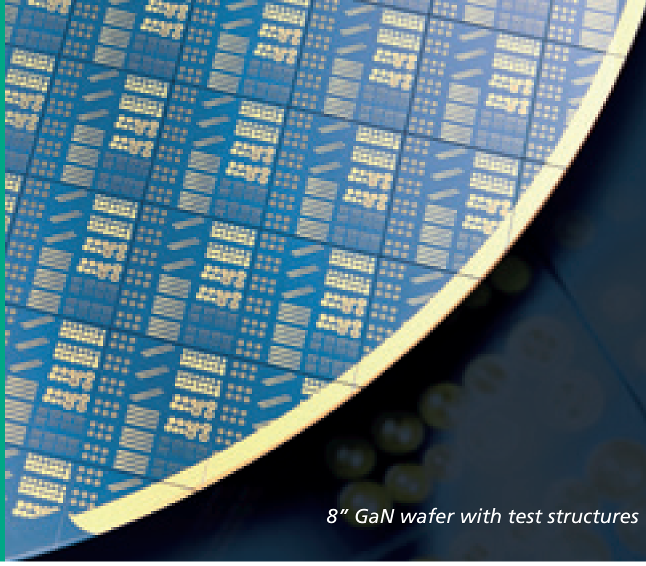
Glass Micromachining

The Fraunhofer ISIT developed a process based on hot temperature viscous glass micromachining. It is mainly used for the production of micro-lenses and glass packages with inclined window surfaces. Using this process, it is possible to structure glass wafers with high aspect ratios on wafer level. A structured silicon wafer is chosen as so-called primitive form, so glasses must be used whose softening temperature is well below that of silicon. This has the advantage that the standardized methods to structured silicon wafers of a clean room can be used. The etched structures or cavities correspond later the molded areas in the glass. The structured silicon wafer is then anodically bonded to a glass wafer. In this case, a defined pressure within the cavities is enclosed. When a relative vacuum is enclosed the cavities and the heat treatment takes place under atmospheric pressure, the glass is pressed into the cavities. If an atmospheric pressure is enclosed and the heat treatment takes place under vacuum then the glass is forced out of the cavities. Depending on the application, the glass may now be further processed by grinding and polishing.

Piezo MEMS Technology Platform

The Fraunhofer ISIT has been working for more than 10 years on the deposition of thin films of the piezoelectric materials aluminum nitride (AlN) and lead zirconium titanate (PZT). Currently, sputtering processes with film thicknesses of up to 4 µm for AlN and up to 3 µm for PZT are available. The integration into MEMS structures is typically realized via unimorphs consisting of a piezoelectric layer embedded between two metal electrodes on top of a passive support layer made from mono- or polycrystalline silicon. PZT is mainly used for actuator applications, as its high piezoelectric coefficients enable particularly large deflections and high forces with only low drive voltages. The PZT actuators are integrated for their utilization in MEMS scanners and loudspeakers. For sensory applications, AlN is preferred due to its considerably better signal-to-noise ratio. At ISIT it is currently used in ultrasonic transducers, MEMS microphones and vibrational energy harvesters. In addition to these established materials scandium-doped AlN (AlScN) is being developed in cooperation with the Christian-Albrecht University of Kiel. Despite the higher piezoelectric coefficients compared to pure AlN, this material retains the advantageous properties (high dielectric strength, IC-compatible, low dielectric losses) of the AlN and is therefore suitable for both sensor and actuator MEMS components. In the long term, it is intended to completely replace the lead-containing PZT. Among other things, a highly sensitive magnetoelectric sensor and MEMS scanners based on AlScN films of higher piezoelectric performance are currently being developed.


NdFeB micromagnets based on innovative powder technology


8″ GaN wafer with test structures

Powder MEMS Technology Platform

At Fraunhofer ISIT a novel technology has been developed which allows the integration of nearly any material onto planar substrates. It is based on the agglomeration of micron-sized powder (particles) by atomic layer deposition (ALD). Like for the fabrication of ceramics, firstly a mold, in this particular case a silicon substrate with dry etched micromold pattern, is filled with loose powder. However instead of sintering the particles together with high pressure at 800°C to 1400°C, the silicon substrate is subjected to an ALD process at much lower temperatures. Thanks to the outstanding coating capability of ALD the loose particles in the micromolds are fixated to porous 3D structures over the whole mold depth (up to 700 µm) by a layer with a thickness of only 75 nm. These porous 3D structures are shrinkage-free and stable mechanically as well as thermally. Lateral dimensions between 50 µm and several mm can be realized with high precision. The nearly perfect envelopment of each particle by the ALD layer ensures an excellent protection against environmental influences. Substrates with embedded porous 3D structures can be post-processed in a cleanroom using standard processes of IC and MEMS fabrication at up to 400 °C. That opens up a unique range of applications. One of the evaluated ones is the fabrication of integrated permanent micromagnets from NdFeB powder. Strong magnetic fields on small scale are of interest for many MEMS sensors and actuators. The focus at ISIT is currently on magnetically driven vibrational energy harvesters and microscanners. Other promising applications of the novel technology are miniaturized organic-free phosphor converters for solid state lighting (SSL) or the thermal isolation of calorimetric MEMS, like mass flow and gas sensors, from the substrate by evacuated porous 3D structures, which is comparable to conventional super vacuum insulation.

GaN Technology

In addition to the research of new high voltage silicon devices the ISIT is developing high voltage devices with gallium nitride (GaN) substrates. This material is used to replace silicon because of higher electric strength, higher switching speed and higher possible working temperature. These benefits lead to a higher efficiency.

While lateral HEMT devices can be purchased today, the research objectives of the ISIT are vertical transistors on 8″ wafer. The substrates of these wafers are made of silicon, only the top layers where the power device is placed in are epitaxial grown GaN.

To achieve the goal, the equipment and know-how of the newly built MEMS cleanroom will be used. Technology is and has been adapted to meet the requirements of the new material. Supplemental equipment to avoid silicon contamination of GaN material (Si is a dopant for GaN) is going to be ordered in the project "Forschungsfabrik Mikroelektronik Deutschland" (FMD). That includes tools for e.g. dry etching, wafer cleaning and annealing.


Lithium polymer cell with integrated reference electrode

FURTHER TECHNOLOGY OFFERS

Metal Surface Micromachining

Metal surface micromachining is an alternative way to build up complete MEMS systems or a part of them. By using mainly electroplating and lithography in combination with PVD, PECVD and etching processes it is possible to fit the requirements for a variety of applications. The low CMOS/ASIC compatible temperature budget makes this process suitable for the monolithical integration of a complete MEMS system. Furthermore, a high flexibility in design and thickness is given. Additional fields of application are electrodes for electrostatic actuation/deflection, bondframes for waferlevel packaging, metal wiring, bondpads, bumps and high-Q inductors

Pouch Cell Technology

Based on the lithium ion battery technology, Fraunhofer ISIT provides a flexible manufacturing platform enabling technical realization of accumulator development. The production of cells can be divided in two main steps:

- Manufacturing of electrodes and separators
- Assembling of cells

The electrodes can be produced with laboratory equipment up to pilot line level with a maximum speed of 2 m/min. In this context the proprietary separator concept developed by Fraunhofer ISIT is an integral part of the cell technology. It is exactly matched to the assembling process (lamination) for the production of cells.

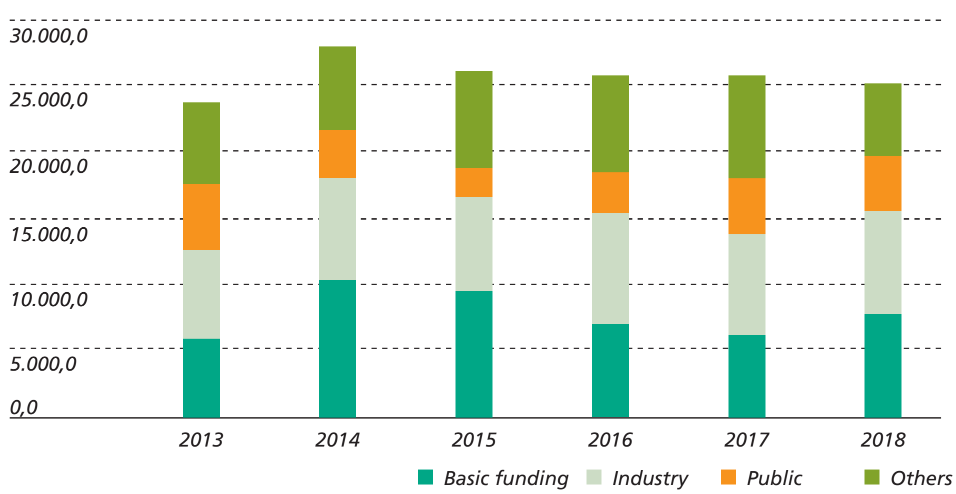
By variation of materials in the lithium accumulator its performance can be controlled within a wide range. In addition, the pouch casing enables an adaption of the cell design in a wide format range to predetermined dimensions. By continuous introduction of new materials a considerable „electrochemical system module" was generated over the years. It is adjusted continuously to increasing requirements.

REPRESENTATIVE FIGURES

BUDGET

Income of Fraunhofer ISIT from 2013 up to 2018
The budget 2018 was financed by proceeds of projects of industry/industrial federations/small and medium sized companies amounting to 7.890,3 T€, of government/project sponsors/ federal states amounting to 4.383,4 T€ and of others amounting to 5.113,2 T€. Furthermore there were FhG-projects and basic funding with 7.429,4 T€.

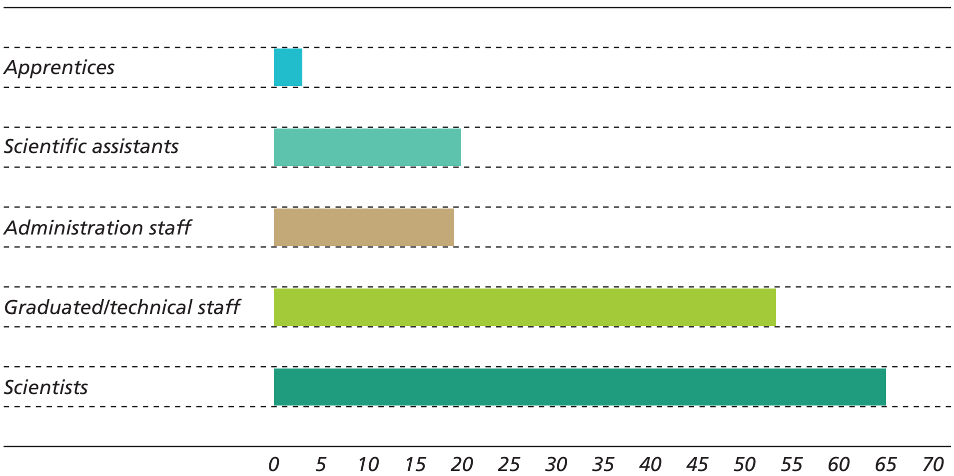
Budget [T€]



Staff Development

At the end of 2018 the staff consisted of 138 full time employees. 65 were employed as scientific personnel, 54 as graduated/technical personnel and 19 worked within organization and administration. The employees were assisted through 20 scientific assistants and 3 apprentices.

Staff Development



RESEARCH FAB MICROELECTRONICS GERMANY – ONE-STOP-SHOP FOR THE COMPLETE MICRO AND NANOELECTRONICS VALUE CHAIN

Fraunhofer ISIT is one of 13 members of the Research Fab Microelectronics Germany (FMD) – Europe's largest cross-location R&D collaboration for microelectronics and nanoelectronics, with over 2000 scientists.

Within this new type of cooperation, the advantages of two strong and decentralized research organizations – the Fraunhofer-Gesellschaft and the Leibniz Association – are combined with the synergies of a central organization to form the world's most capable provider of applied research, development, and innovation within microelectronics and nanoelectronics. The close intermeshing and the uniform public face allow the FMD to serve not only customers from heavy industry, but also to offer SMEs and startups more comprehensive and simpler access to the next generation of technology.

The German Federal Ministry of Education and Research (BMBF) is funding the setup of the FMD to the tune of 350 million euros, largely in the modernization of the institutes' research equipment. With this funding, the BMBF intends to strengthen the innovativeness of the German and European semiconductor and electronics industry and is supporting the initiative with the largest investment in research devices since Germany was reunified.

A year and a half after the project started on April 6, 2017, a lot of new acquisitions for the modernization of the laboratory facilities at FMD's locations around Germany went into operation. The ceremonial opening of the first integration line was on September 28, 2018, as part of the 1st FMD Innovation Day at the Berlin-based Fraunhofer Institute for Reliability and Microintegration IZM, which hosted the event on behalf of all members.

At around the halfway point of the project, 45 percent of the planned investments for the FMD have been successfully fulfilled.

The setup of the Research Fab Microelectronics Germany is coordinated in a central business office in Berlin, although – true to the concept of a virtual organization – additional locations in Dresden and Munich have also been opened. The FMD business office is the central contact point for potential and existing customers and is thus a significant driver of the development of the business in the area of microelectronics and nanoelectronics. In order to be able to offer nationally coordinated technology and system developments from a single provider, the technological expertise of the institutes was grouped into six overarching areas – the technology platforms known as Microwave and Terahertz / Power Electronics / Extended CMOS / Optoelectronic Systems / Sensor Systems / MEMS Actuators. Within these technology platforms, the FMD offers the market technological developments along the entire value creation chain, from system design to testing and reliability.

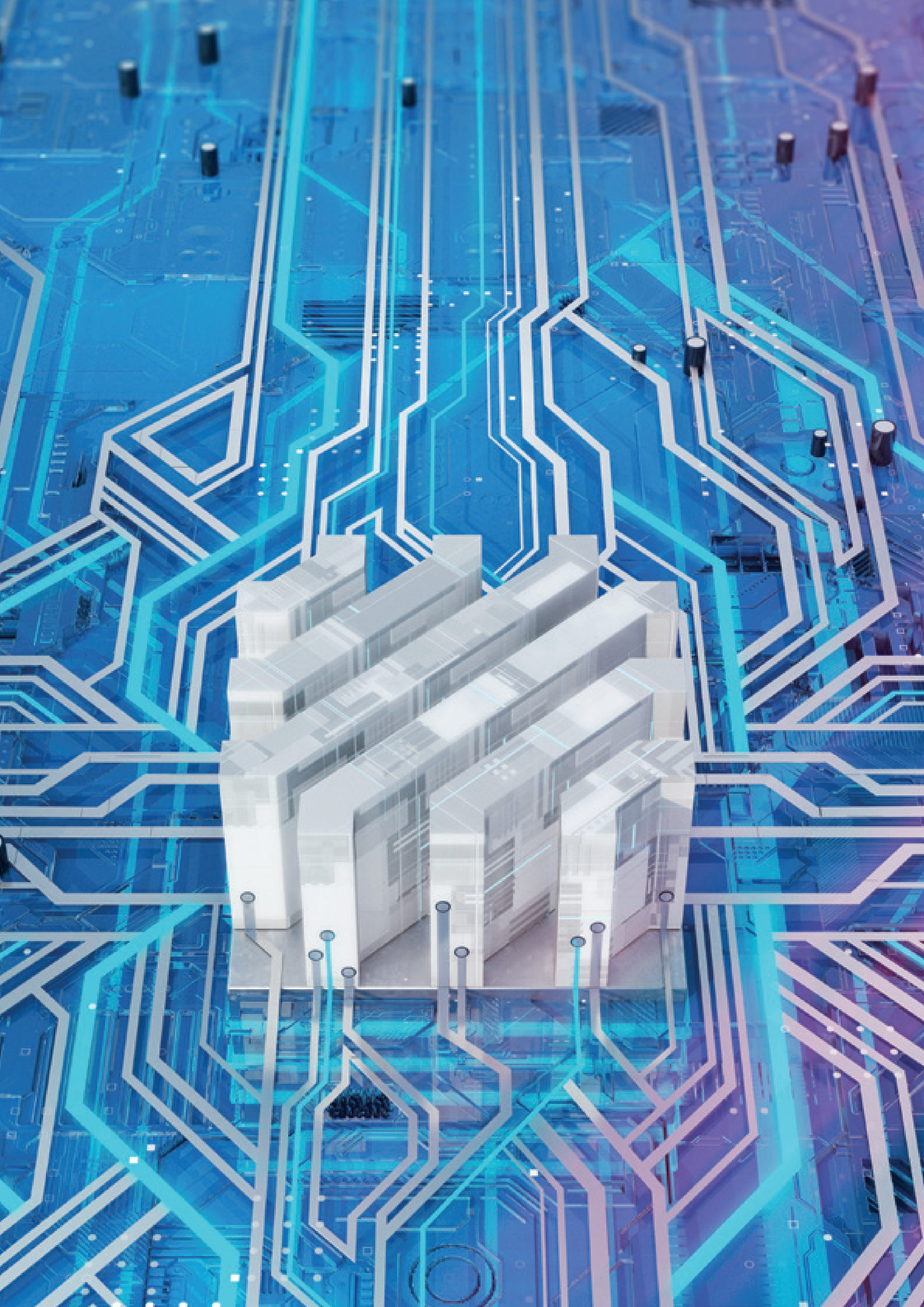
In addition to these technologically oriented offerings, the FMD also offers cross-institute application solutions from a single provider. This offers customers a way of realizing combined and optimized system solutions together the FMD and its institutes. In doing so, the Research Fab works in synergy with the business units of all institutes involved. We, as the FMD, can thus offer our customers a wider range of application solutions.

In 2017, successful project involvements were set up and orders were completed in combination with the FMD. For 2018, projects based on the FMD investments with a volume of 41.1 million euros can already be identified, which represents a significant success at such an early stage. The industrial share of this project volume is already at 30 percent, which highlights the importance of this unique cooperation in German microelectronics research to industry.

In 2019, the Research Fab Microelectronics Germany will enter the next phase. After establishment and structuring of the organization, the largest cross-location R&D collaboration for microelectronics and nanoelectronics in Europe, in partnership with its institutes, will prove its mettle on the market.

Fraunhofer ISIT
is participant of the

Forschungsfabrik
Mikroelektronik
Deutschland



THE FRAUNHOFER-GESELLSCHAFT

Research of practical utility lies at the heart of all activities pursued by the Fraunhofer-Gesellschaft. Founded in 1949, the research organization undertakes applied research that drives economic development and serves the wider benefit of society. Its services are solicited by customers and contractual partners in industry, the service sector and public administration.

At present, the Fraunhofer-Gesellschaft maintains 72 institutes and research units. The majority of the more than 26,600 staff are qualified scientists and engineers, who work with an annual research budget of 2.6 billion euros. Of this sum, 2.2 billion euros is generated through contract research. Around 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Around 30 percent is contributed by the German federal and state governments in the form of base funding, enabling the institutes to work ahead on solutions to problems that will not become acutely relevant to industry and society until five or ten years from now.

International collaborations with excellent research partners and innovative companies around the world ensure direct access to regions of the greatest importance to present and future scientific progress and economic development.

With its clearly defined mission of application-oriented research and its focus on key technologies of relevance to the future, the Fraunhofer-Gesellschaft plays a prominent role in the German and European innovation process. Applied research has a knock-on effect that extends beyond the direct benefits perceived by the customer: Through their research and development work, the Fraunhofer Institutes help to reinforce the competitive strength of the economy in their local region, and throughout Germany and Europe. They do so by promoting innovation, strengthening the technological base, improving the acceptance of new technologies, and helping to train the urgently needed future generation of scientists and engineers.

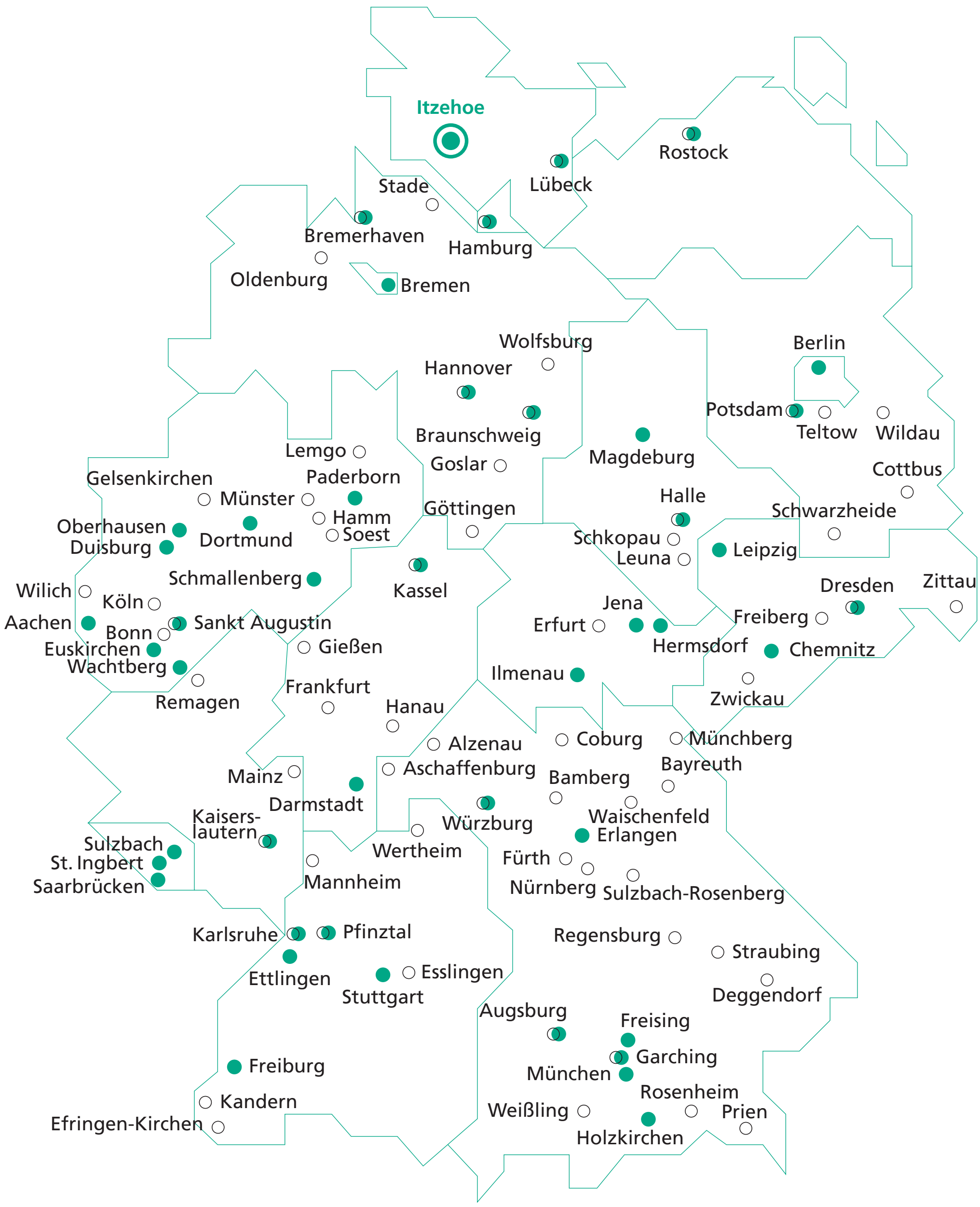
As an employer, the Fraunhofer-Gesellschaft offers its staff the opportunity to develop the professional and personal skills that will allow them to take up positions of responsibility within their institute, at universities, in industry and in society. Students who choose to work on projects at the Fraunhofer Institutes have excellent prospects of starting and developing a career in industry by virtue of the practical training and experience they have acquired.

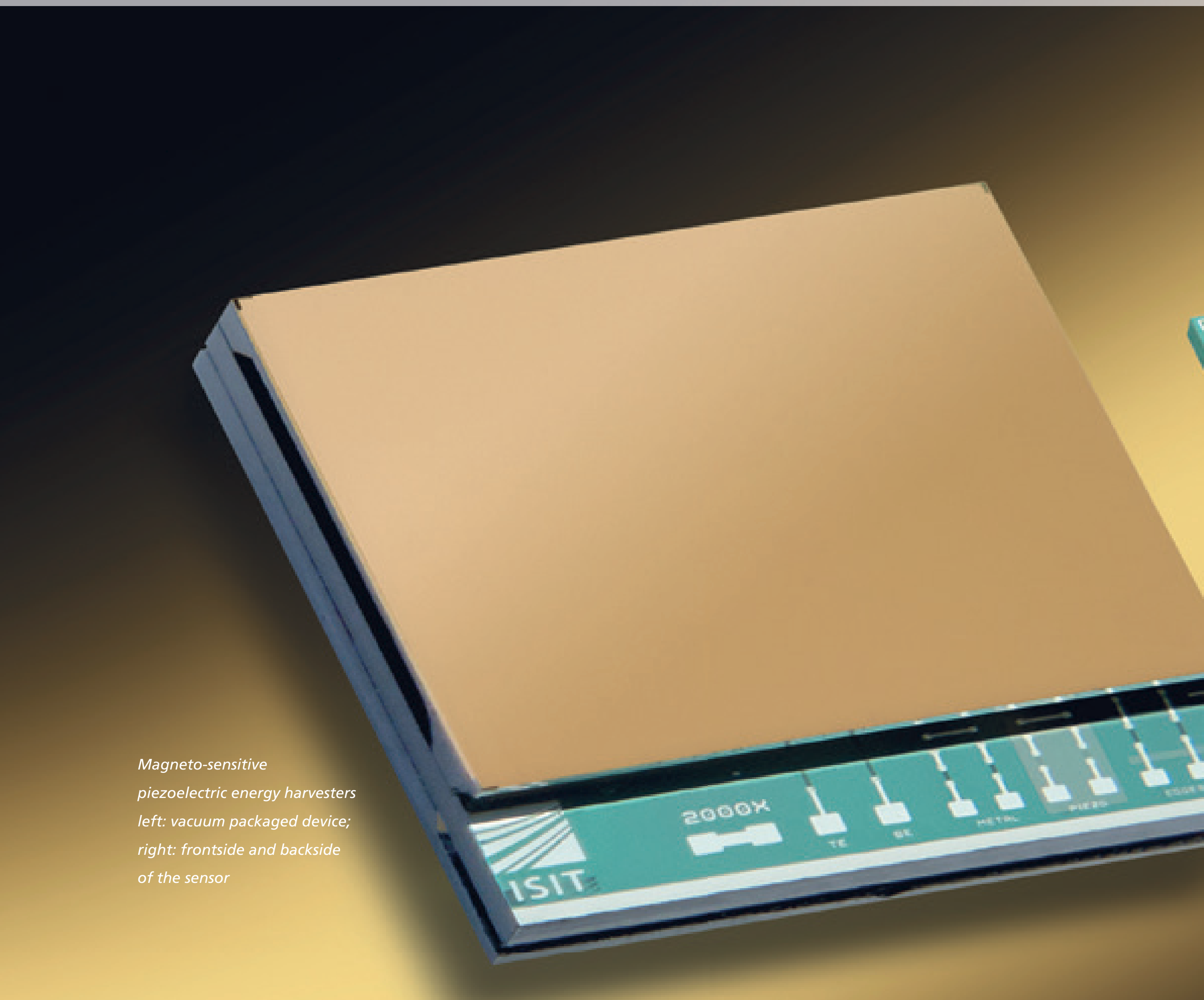
The Fraunhofer-Gesellschaft is a recognized non-profit organization that takes its name from Joseph von Fraunhofer (1787–1826), the illustrious Munich researcher, inventor and entrepreneur.

LOCATIONS OF THE RESEARCH FACILITIES

● Main Location

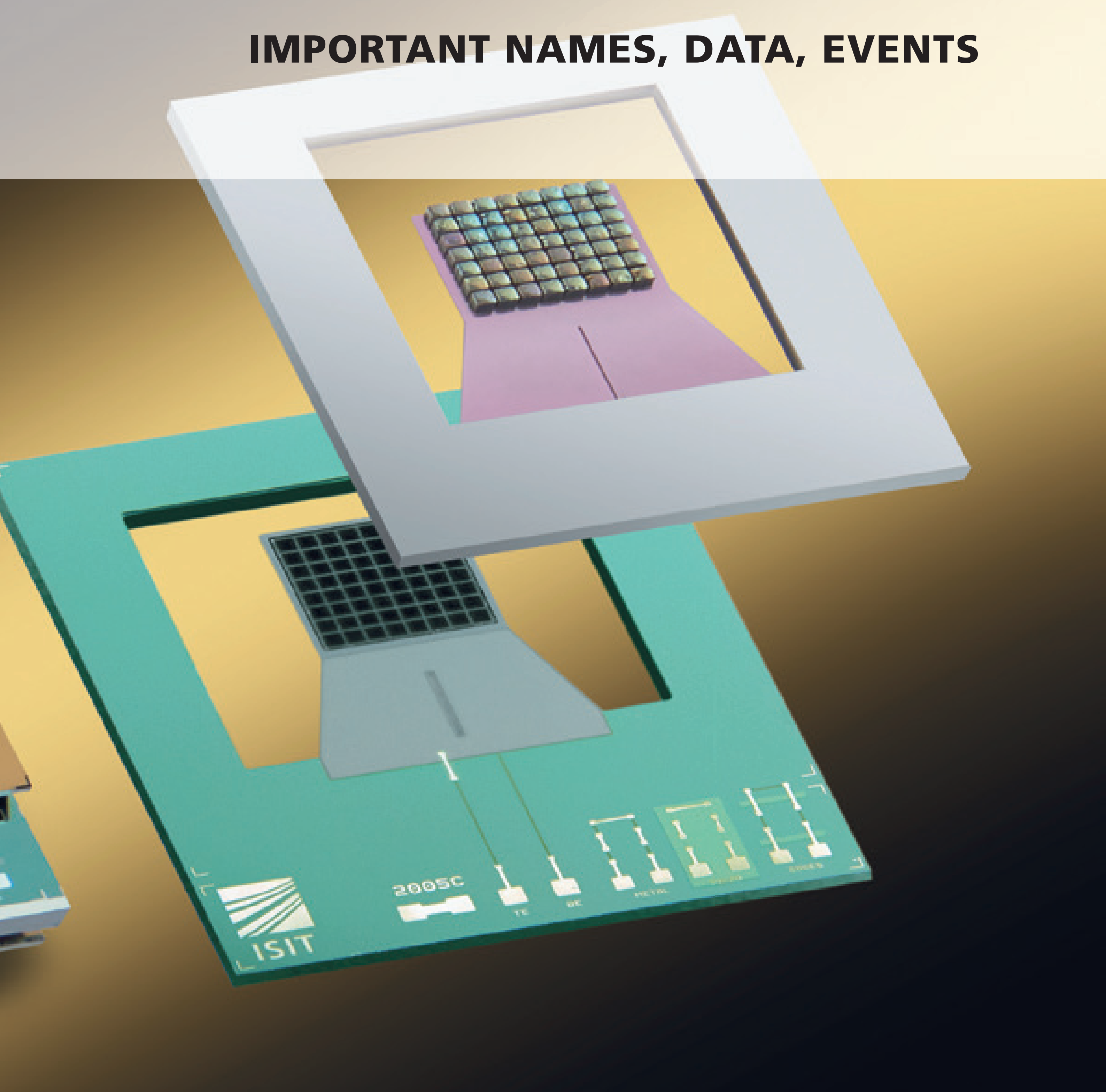
○ Other Location





Magneto-sensitive piezoelectric energy harvesters left: vacuum packaged device; right: frontside and backside of the sensor

IMPORTANT NAMES, DATA, EVENTS



Cooperation with Institutes and Universities

Technische Universität Carolo-Wilhelmina zu Braunschweig, Braunschweig

Technische Universität Dresden

Albert-Ludwigs-Universität, Freiburg

Universität Graz, Austria

Hochschule für Angewandte Wissenschaften, Hamburg

Fachhochschule Westküste, Heide

Hochschule Kaiserslautern

Karlsruhe Institute of Technology – KIT, Karlsruhe

Christian-Albrechts-Universität, Technische Fakultät, Kiel

Fachhochschule Kiel

Fachhochschule Lübeck

Westfälische Wilhelms-Universität – Münster Electrochemical Energy Technology, Münster

Universität Siegen

DLR, Stuttgart

Helmholtz Institute Ulm (HIU) – Electrochemical Energy Storage, Ulm

Lecturing Assignments at Universities

W. Benecke
Lehrstuhl Technologie Silizium-basierter Mikro- und Nanosysteme,
Technische Fakultät, Christian-Albrechts-Universität zu Kiel

R. Dudde
Mikrotechnologien (8168), Fachbereich Technik,
FH Westküste, Heide

F. Haase
Professor für Leistungselektronik und Grundlagen der Elektrotechnik,
Department Informations- und Elektrotechnik, HAW Hamburg

H. Kapels
Professur Halbleiterbauelemente der Leistungselektronik,
Technische Fakultät, Christian-Albrechts-Universität zu Kiel

G. Pangalos
Advanced Control Systems: Simulation and Optimization Tools,
Lehrauftrag an der HAW Hamburg

O. Schwarzelbach
Mikrosystementwurf,
Fachbereich Technik, FH Westküste, Heide

O. Schwarzelbach
Mikroelektromechanische Systeme (MEMS),
Institut für elektrische Messtechnik und Mess-Signalverarbeitung, Technische Universtität Graz, Austria

B. Wagner
Lehrstuhl Prozesse und Materialien der Nanosystemtechnik,
Micro- and Nanosystem Technology, Technische Fakultät, Christian-Albrechts-Universität zu Kiel

Distinctions

Katja Reiter, Sebastian Puls
Buehler-Preis 2018,
Best Paper Awards
Third Place for Article
"Metallographische Untersuchung von Brandschäden in der Elektronik",
September 20, 2018,
Leoben, Austria

Carlos Cateriano Yáñez
Second Place for
Best Poster at Dies Academicus 2018 for
"Power Quality Compensation for Smart Grids by Model Predictive Control",
October 23, 2018,
HAW Hamburg, Hamburg

Memberships in Coordination Boards and Committees

W. Benecke
Member of Programming Committees of:
- IEDM (International Electron Devices Meeting)
- EUROSENSORS
- ESSDERC (European Solid-State Device Conference)
- ESSCIRC (European Solid-State Circuits Conference)
- MST Kongress

W. Benecke
Member of Editorial Boards
- 'Sensors & Actuators'
- Microsystem Technologies (MST)

L. Bertels
Member of Deutsche Gesellschaft für Qualität – DGQ kooperative Firmenmitgliedschaft

L. Bertels
Member of DGQ-Qualitätsleiterkreis Hamburg

L. Bertels
Member of DGQ-Regionalkreis Hamburg and Schleswig-Holstein

L. Bertels
Member of Network „Qualitätsmanagement" of the Fraunhofer Gesellschaft

R. Dudde
Member of IVAM e.V. – Fachverband für Mikrotechnik

J. Eichholz
Member of GMM/GI-Fachausschuss EM „Entwurf von Mikrosystemen", VDE/ VDI-Gesellschaft für Mikroelektronik, Mikro- und Feinwerktechnik

J. Hagge
Member of GfKORR Arbeitskreis „Korrosionsschutz in der Elektronik und Mikrosystemtechnik"

U. Hofmann
Member of Programm Committee „MOEMS and Miniaturized Systems Conference", OPTO, Photonics West, San Francisco

H. Kapels
Member of Erneuerbare Energien Hamburg e.V. – EEHH

T. Knieling
Member of Organic and Printed Electronics North (OPEN)

M. Kontek
Member of AG 2.4 Drahtbonden, DVS

M. Kontek
Member of
AG 2.7 Kleben in der Elektronik und Feinwerktechnik, DVS

J. Lähn
Member of Hamburger Lötzirkel

R. Mörtel
Member of Bundesverband Energiespeicher (BVES)

R. Mörtel
Member of Fraunhofer-Allianz Energie

R. Mörtel
Member of Fraunhofer-Allianz Batterien

R. Mörtel
Member of Subsea of the Fraunhofer Gesellschaft

A. Müller-Groeling
Member of NiNa Norddeutsche Initiative Nanotechnologie e.V.

M. H. Poech
Member of Arbeitskreis „Systemzuverlässigkeit von Aufbau- und Verbindungstechnologie"
des Fraunhofer IZM

W. Reinert
Member of Arbeitskreis A2.6, "Waferbonden", DVS

W. Reinert
Member of DVS-Fachausschuss FA10 "Mikroverbindungstechnik"

W. Reinert
Member of Technical Committee of Electronics Packaging Technology Conference (EPTC)-Singapore

W. Reinert
Member of GMM Workshop Packaging von Mikrosystemen

W. Reinert
Member of Wafer Bond Technologie Konferenz

W. Reinert
Member of ZVEI Arbeitskreis Packaging

W. Reinert
Meber of IEC:TC 119 „Printed Electronics"/ DKE/ GUK 682.1 „Gedruckte Elektronik"

K. Reiter
Member of DGM, Arbeitskreis Probenpräparation

K. Reiter
Member of Metallographie Nord

K. Reiter
Member of „Preparation-Board“ Praktische Metallographie

H. Schimanski
Member of VDE/VDI Arbeitskreis „Prüftechniken in der Elektronikproduktion“

H. Schimanski
Member of ZVEI Fachverband Arbeitsgruppe „Zuverlässigkeit von Leiterplatten“

H. Schimanski
Member of Hamburger Lötzirkel

H. Schimanski
Member of FED Arbeitskreis „Baugruppe“

H. Schimanski
Member of FED Regionalgruppe Hamburg

H. Schimanski
Member of DVS Fachausschuss FA10 „Mikroverbindungs-technik“

H. Schimanski
Member of GfKORR Arbeits-kreis „Korrosionsschutz in der Elektronik und Mikrosystem-technik“

H. Schimanski
Member of IMAPS Deutschland

H. Schimanski
Member of ZVEI Ad-hoc Arbeitskreis „Repair und Rework von elektronischen Baugruppen“

S. Schröder
Member of Arbeitskreis 2.4 Drahtbonden, DVS

S. Schröder
Member of IMAPS Deutschland

V. Stenchly
Senior Advisor GMM VDE/VDI- Gesellschaft für Mikroelektronik, Mikro- und Feinwerktechnik

B. Wagner
Member of GMM-Fach-ausschuss 4.1 „Grundsatz-fragen der Mikrosystemtechnik und Nanotechnologie“, VDE/ VDI-Gesellschaft für Mikroelektronik, Mikro- und Feinwerktechnik

B. Wagner
Member of AMA Verband für Sensorik und Messtechnik e.V.

A. Würsig
Member of Allianz Batterien of the Fraunhofer-Gesellschaft

A. Würsig
Member of Allianz Energie of the Fraunhofer-Gesellschaft

A. Würsig
Member of Bundesverband Energiespeicher (BVES)

A. Würsig
Member of Kompetenznetz-werk Lithium-Ionen-Batterien (KLiB)

A. Würsig
Member of Subsea of the Fraunhofer-Gesellschaft

G. Zwicker
Head of Fachgruppe Planarisie-rung/ Fachausschuss Verfahren/ Fachbereich Halbleitertech-nologie und -fertigung der GMM des VDE/VDI

G. Zwicker
Member of International Executive Committee of International Conference on Planarization/CMP Technology (ICPT)

Trade Fairs and Exhibitions

Nortech 2018
January 23–26, 2018,
Hamburg

SPIE 2018
Photonics West Exhibition,
January 30– February 01, 2018,
San Francisco, USA

Battery Japan 2018
International Rechargeable
Battery Expo,
February 28– March 02, 2018,
Japan

Battery & Storage 2018
March 13–15, 2018,
Düsseldorf

Energy Storage Europe 2018
March 14–16, 2018,
Düsseldorf

DAGA 2018
Deutsche Jahrestagung
der Akustik,
March 19–22, Munich

Hannover Messe 2018
Leading Trade Show for
Integrated Energy Systems for
Industry, Heating and Mobility,
April 23–27, 2018,
Hannover

Nordjob Unterelbe Westküste 2018
Fair for Education and Study,
May 29–30, 2018,
Brokdorf

PCIM 2018
International Exhibition &
Conference, Power Conversion
Intelligent Motion,
June 04–08, 2018,
Nuremberg

SMT/Hybrid/Packaging 2018
Hybrid Packaging System
Integration in Micro Electronics,
June 05–07, 2018,
Nuremberg

ees Europe 2018
Trade Fair for Electrical Energy
Storage,
June 20–22, 2018, Munich

CIOE Shenzhen
International Optoelectronic
Expo,
September 05–08, 2018,
Shenzhen, China

microtec nord 2018
September 13, 2018, Heide

AzubIZ 2018
Regional Recruiting Fair,
September 21, 2018, Itzehoe

WindEnergy 2018
The Global On & Offshore
Expo,
September 25–28, 2018,
Hamburg

FMD Innovation Day 2018
Exhibition of the Forschungs-
fabrik Mikroelektronik
Deutschland,
September 27–28, 2018,
Fraunhofer IZM, Berlin

Electronica 2018
World's Leading Trade Fair and
Conference for Electronics,
November 12–16, 2018,
Munich

Miscellaneous Events

International Workshop on Piezoelectric MEMS
January 15–16, 2018, Orlando, USA

International Conference on Micro Electro Mechanical Systems (MEMS 2018)
January 21–25, 2018, Belfast, Northern Ireland

ISIT Presentation in Framework of „Macht mit bei MINT–Zukunftsberufe für Frauen“
Information Day for Schoolgirls, initiated by Volkshochschulen Kreis Steinburg,
February 20, 2018,
Fraunhofer ISIT, Itzehoe

EMC in Industrial Electronics
Danfoss Silicon Power,
February 27, 2018, Flensburg

Fachtagung Energieautonome Sensorsysteme
February 28–March 1, 2018,
Dresden

3rd On-Site Lithium-Ion Cell Production Technology
CCI Seminar,
April 4–5, 2018,
Fraunhofer ISIT, Itzehoe

ISIT-Lotpasten-applikationstage
Technology Event
April 18–19, 2018,
Fraunhofer ISIT, Itzehoe

European Embedded Control Institute (EECI), International Graduate School on Control (IGSC)
Model Predictive Control,
April 23–27, 2018,
Paris, France

Science Reception of the State Government of Schleswig Holstein
Speakers: Daniel Günther,
Prime Minister,
Prof. Isabelle Peters, Central Library of Economics and
Dr. Axel Müller-Groeling,
May 31, 2018,
Fraunhofer ISIT, Itzehoe

Internal Workshop Netzwerk Leistungselektronik Schleswig Holstein „Akteure stellen ihre Unternehmen vor“
June 01, 2018, Itzehoe

ECPE-Schulung „Model Predictive Control for Power Electronics, Drives, and Power Grid Applications“
June 02–03, 2018, Frankfurt

European Control Conference 2018 (ECC18)
June 12–15, 2018,
Limassol, Zypern

ISIT Presentation for the CDU Parliamentary Group in Schleswig-Holstein
Speakers:
Dr. Axel Müller-Groeling and
Dr. Andreas Würsig,
July 11, 2019,
Fraunhofer ISIT, Itzehoe

8th International Conference on Simulation and Modeling (Simultech 2018)
July 29–31, 2018,
Porto, Portugal

ECPE-Schulung „Passives in Power Electronics“
September 10–11, 2018,
DTU Kopenhagen, Dänemark

DVN Conference: Lidar Synergies With Lighting
September 19–20, 2018,
Frankfurt-Sulzbach

NEIS 2018
September 20–21, 2018,
Helmut-Schmidt-Universität (HSU), Hamburg

Statusseminar Batterie 2020 – Project Presentation HiPoLiT und MagS
October 10–11, 2018, Köln

AES Convention
October 17–20, New York, USA

4th On-Site Lithium-Ion Cell Production Technology
CCI Seminar,
October 23–24, 2018,
Fraunhofer ISIT, Itzehoe

2 nd Workshop Netzwerk Leistungselektronik Schleswig-Holstein „DC-Netz-Versorgung, Applikationen und Sicherheitsaspekte der Zukunft“
October 26, 2018, Neumünster

NEW 4.0 Workshop „Stromnetze unter Spannung“
November 20, 2018,
Hotel Kieler Yacht Club, Kiel

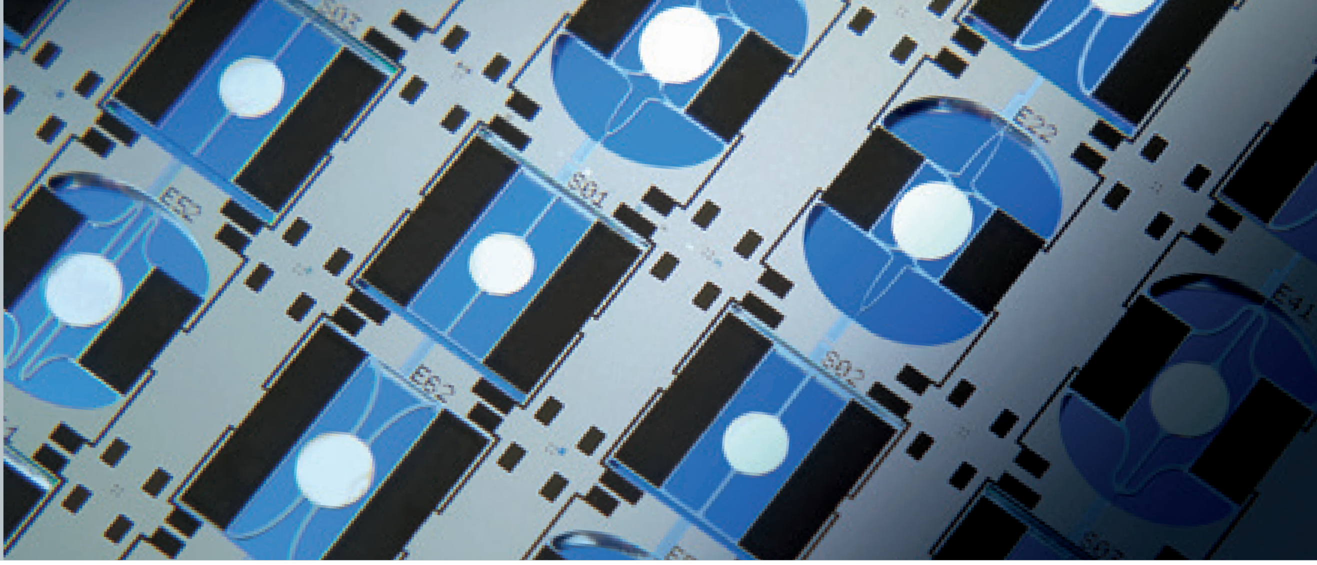
MRS Fall Meeting 2018
November 25–30, 2018,
Boston, USA

Forum Elektromobilität Schleswig-Holstein
December 03, 2018,
Sparkassenarena, Kiel

Science Match – **Future Energies**
December 04, 2018,
Sparkassenarena, Kiel

NEW 4.0 Transferworkshop
December 05, 2018,
Hamburg

Project Presentation at InnoTruck, a Road Show Exhibition of the Federal Government in the Frame of the Project „HiPoLiT-Schnellladefähige Lithium-Energiespeicher mit verbesserter Energiedichte für den Einsatz in modularen Unterstützungs- und Antriebskonzepten“
2018



Patents

Supplement 2017

W. Reinert, H.J. Quenzer
Housing for an Infrared Radiation Micro Device and Method for Fabricating Such Housing
KR 10-1805895

2018

W. Reinert, J. Quenzer, K. Gruber, S. Warnat
Method for Forming a Micro-Surface Structure and for Producing a Micro-Electromechanical Component
US 9,637,377 B2

T. Lisec, E. Nebling, S. Kubick, S. Rupp
Verfahren zur Herstellung eines Bauelements auf Basis eines strukturierbaren Substrats mit dreidimensionaler, Poren im nm-Bereich aufweisender Membranstruktur
DE 102015101425 B4

H. J. Quenzer, U. Hofmann, V. Stenchly
Method for Producing Structured Optical Components
US 9,910,273 B2

S. Gu-Stoppel, H.J. Quenzer, U. Hofmann
Vorrichtung mit einem schwingfähig aufgehängten optischen Element und Verfahren zum Auslenken desselben
DE 102013206788 B4

U. Hofmann
Micromechanical Resonator Arrangement
JP 6289067

U. Hofmann, F. Senger, T. v. Wantoch, C. Mallas, J. Janes, M. Weiß
Verfahren zum Ansteuern einer Ablenkeinrichtung für eine Projektionsvorrichtung, Ablenkeinrichtung für eine Projektionsvorrichtung und Projektionsvorrichtung
CN ZL201510646796.2

U. Hofmann
Microactuator Arrangement for Deflecting Electromagnetic Radiation
US 9,910,267 B2
CN ZL201510646796.2

Z. Yu, K.F. Hoffmann, H. Kapels
DC-DC Converter with Inductor Current Direction Reversed Each Switching Period
US 9,923,466 B2

S. Gu-Stoppel, H.J. Quenzer, J. Janes
Vorrichtung mit einem schwingfähig aufgehängten optischen Element
DE 102013209234 B4

S. Gu-Stoppel, D. Kaden, C. Eisermann
Vorrichtung mit einer Feder und einem daran aufgehängten optischen Element
CN ZL2014102346714
US 10,095,023 B2

W. Reinert, P. Merz
In der Mikrosystemtechnik einsetzbares Bauelement sowie Lötverfahren zum Verbinden entsprechender Wafer- bzw. Bauelement-Teile
EP 1945563 B1

U. Hofmann, M. Weiss, J. Janes, F. Senger
Radiation Imaging Sensor
US 10,041,837 B2

N. Marenco, H.-J. Quenzer
Verfahren zum Strukturieren eines aus glasartigem Material bestehenden Flächensubstrats sowie optisches Bauelement
EP 2742009 B1

T. Lisec, M. Knez
Verfahren zum Erzeugen einer dreidimensionalen Struktur sowie dreidimensionale Struktur
EP 2670880 B1

J. Janes
Projektionsvorrichtung und Verfahren zum Abtasten eines Raumwinkelbereichs mit einem Laserstrahl
DE 102017200691 B4

Z. Yu, H. Kapels, K. Hoffmann
Stromrichterschaltung und Verfahren zur Steuerung derselben
DE 102016125796 B3

N. Laske, H.J. Quenzer, V. Stenchly, A. Kulkarni, A.-V. Schulz-Walsemann
Verfahren zur Herstellung von plankonvexen Linsenelementen und zur Herstellung eines gehäusten Bauelements auf Waferebene
DE 102017213065 B3

W. Reinert, H.J. Quenzer
Method of Producing a Cap Substrate, and Packaged Radiation-Emitting Device
US 9,912,115 B2

S. Gu-Stoppel, H.-J. Quenzer, J. Janes, F. Heinrich
Piezoelectric Position Sensor for Piezoelectrically Driven Resonant Micromirrors
US 10,101,222 B2

Doctoral Theses

Tim Hinrich Reimer
Neuartige poröse Strukturen für MEMS: Erzeugung per Pulveragglomeration mittels ALD
Christian-Albrecht-Universität zu Kiel, 2018

Diploma, Master's and Bachelor's Theses

Ali Aneissi
Development of a Testbench for the Control of a Low-Voltage E-Machine using Rapid Prototyping
Master's thesis, HAW Hamburg, 2018

Lars Boie
Optimierung und Analyse von Silbersinterprozessen und deren Fehlermechanismen
Bachelor's thesis, Fachhochschule Westküste, January 2018

Julian Franz
Development of a Concept for Supplying System Inertia by Battery Energy
Master's thesis, HAW Hamburg, 2018

Linda Marlen Gosau
Druckbare Batterien – Stand der Technik, Applikationen und Perspektiven
Bachelor's thesis, Fachhochschule Westküste, February 2018

Pascal Jeworek
Entwicklung einer 2,45 GHz Antenne zur Integration in eine Leichtbau-Komponente aus überwiegend Carbonfaser-Verbundwerkstoff
Master's thesis, Fachhochschule Westküste, January 2018

Sripathi Raja Jeyakumar
Screen Printing of Capactive Sensors for Gait Analysis
Master's thesis, Technische Universität Chemnitz, April 2018

Felix Manthey
State-Feedback Control of a Soft Switching Solar Inverter with Resistive Load Including MPPT
Master's thesis, HAW Hamburg, 2018

Marcel Metschulat
Entwicklung und Einsatz eines Steuerungsalgorithmus für einen Balancer eines 14-Zellen-Li-Ion-Akkumulators
Bachelor's thesis, Fachhochschule Westküste, January 2018

Michel Petersen
Experimentelle Untersuchungen und Prozessentwicklung zur Direktmontage von Siliziumchips auf Stahl durch Weichlöten und Demonstration an einer Wägezelle
Bachelor's thesis, Fachhochschule Lübeck, January 2018

Sören Queck
Erweiterung eines Lastwechselmessstandes für das Testen von SiC-MOSFETs
Bachelor's thesis, Fachhochschule Westküste, January 2018

Jose Pablo de los Reyes Helices
VHDL Design & Implementation of High-Speed Laser Control for RGB Projection Device
Master's thesis, CAU zu Kiel, November 2018

Jörg Richter
Model Predictive Controller Tuning in Electrical Distribution Grids by Multiobjective Optimization
Master's thesis, HAW Hamburg, 2018

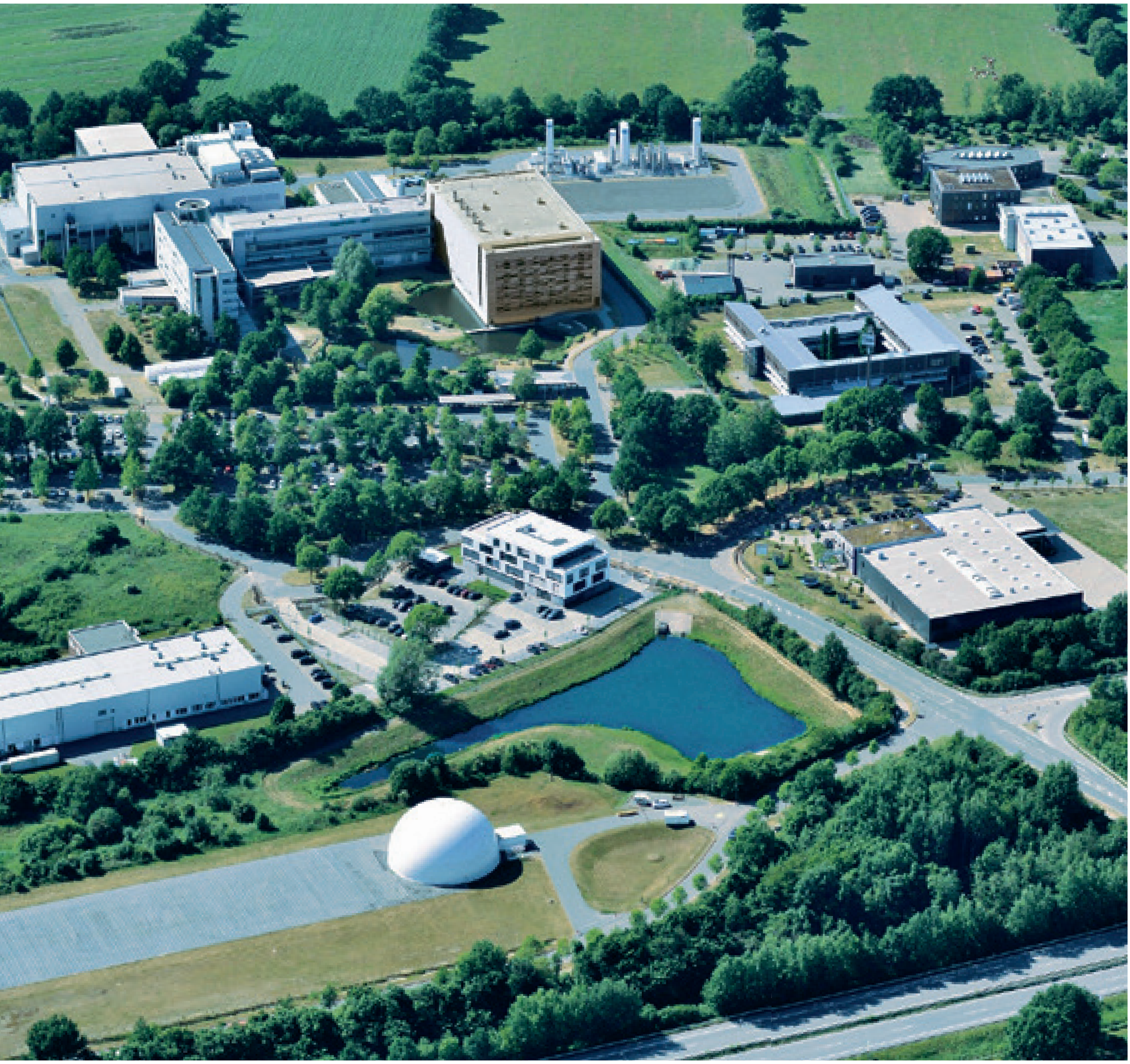
Lena Schartow
Entwicklung eines Kalman-Filters zur Echtzeitanalyse des „runden Tritts" im Radsport, insbesondere bei Straßenfahrten mit Rennrädern
Bachelor's thesis, Hochschule Koblenz, March 2018

Anton Ulrich Stonjek
Ohmsche Kontakte auf p- und n-dotiertem Galliumnitrid für vertikale Bauelemente
Master's thesis, Technische Universität Braunschweig, Institut für Halbleitertechnik, May 2018

Kathrin Weihe
Amplitude Control of a State Signal Shaping Model Predictive Controller for Power Quality Compensation in Distribution Grids
Master's thesis, HAW Hamburg, 2018

Marc-Kevin Wilde
Analyse von Komponentenzertifikaten durch Modellbildung eines EZA-Reglers und Integration in den Anlagenzertifizierungsprozess
Bachelor's thesis, CAU zu Kiel, May 2018

Henri Zeller
Market Possibilities and Regulatory Obstacles for Frequency-Stabilization Measures in the Power Grid
Master's thesis, HAW Hamburg, 2018



Journal Papers, Publications and Contributions to Conferences

H. Hanssen, D. Friedrich, W. Benecke
Technology and Electrical Characterization of MemFlash Cells for Neuromorphic Applications.
Journal of. Physics. D: Applied Physics. 51 (2018) 324003

A. Kulkarni, P. Malaurie, V. Stenchly, H. J. Quenzer, N. Laske, R. Dudde
Silicon Lens Arrays for Wafer Level Packaging of IR-Sensors. TechConnect Briefs 2018, Informatics, Electronics and Microsystems, p.p. 147–150, 2018, ISBN: 978-0-9988782-1-8

F. Manthey, A. Gorodnichev, E. Langnes, G. Pangalos, F. Haase
Model-Based Control of an Inverter for Wide Range Soft-Switching Operation. PCIM 2018, 2018, Nuremberg

A. Männchen, F. Stoppel, D. Beer, F. Niekiel, J. Nowak, B. Wagner
Zwei-Wege-Lautsprecher basierend auf MEMS-Technologie. 44. Deutsche Jahrestagung der Akustik, DAGA 2018, March 19–22, 2018, Munich

A. Männchen, F. Stoppel, D. Beer, F. Niekiel, B. Wagner
In-Ear Headphone System with Piezoelectric MEMS Driver. Audio Engineering Society, Convention e-Brief 469, October 07, 2018

J. Ophey[a], S. Reuber[b], J. Seeba[b], C. Heubner[c], N. Junker[c]
[a]Fraunhofer ISIT, [b]Fraunhofer IKTS, [c]Technische Universität Dresden.
Umweltfreundliche Hoch-Energie-NCM 622-Kathoden mit optimierter Speicherkapazität. ProZell Industrietag 2018, September 10, 2018, Braunschweig

M. Päsler
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R. Dudde
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S. Fichtner
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J. Franz, H. Zeller
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- Herstellung von Kupfermetallisierungen auf Leistungsbauelementen mittels kaltaktiven Atmosphärenplasmas – AIF-Herkules
- Netzwerk Leistungselektronik - Netzwerk LE
- Schaufenster intelligente Energie, Teilvorhaben 3.7, Systemdienstleistungen mit Speichern, Teilvorhaben 4.1, Algorithmen-Entwicklung, Teilvorhaben 8.1, Modellbildung und Simulation zur Systemintegration
- Norddeutsche Energiewende 4.0 – NEW 4.0
- Fraunhofer Anwendungszentrum Leistungselektronik für regenerative Energiesysteme, ALR, Standort Hamburg – ALR
- Integrierte Umrichter für modularverteilte Elektroantriebe hoher Drehzahl - InMOVE; Teilvorhaben: Simulation, Technologische Sonderprozesse und Zuverlässigkeitsuntersuchungen für integrierte Umrichter
- Vertikale GaN MOSFETs für effiziente Leistungselektronik im Niederspannungsbereich – VERTIGO
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- Sub-Mikrometer Mikroplastik Partikel in der marinen Umwelt – Size is Important
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- Schnellladefähige Lithium-Energiespeicher mit verbesserter Energiedichte für den Einsatz in modularen Unterstützungs- und Antriebskonzepten – HiPoLit
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- Hochstromfähiges Lithium-Batteriemodul, Entwicklung einer Hochleistungs-Lithiumbatterie – AIF-Hochleistungsbatterie
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- Erstellen einer Technologieübersicht im Bereich der Lithium-Festkörperbatterien – Traktionsbatterie
- Kostensenkung und Qualitätssteigerung bei der Lithium-Ionen-Batterie-Elektrodenfertigung durch quantitative, optische inline-Messtechnik – Q-LIB
- High Load Cathodes – HiLo, Umweltfreundliche Hoch-Energie-NCM 622-Kathoden mit optimierter Speicherkapazität
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- High Energy Lithium Sulphur Cells and Batteries – HELIS
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- Resonant Magnetoelectric Sensors, Sonderforschungsbereich 1261-A3,
- MEMS Magnetoelectric Sensor Fabrication, Sonderforschungsbereich 1261-Z1
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