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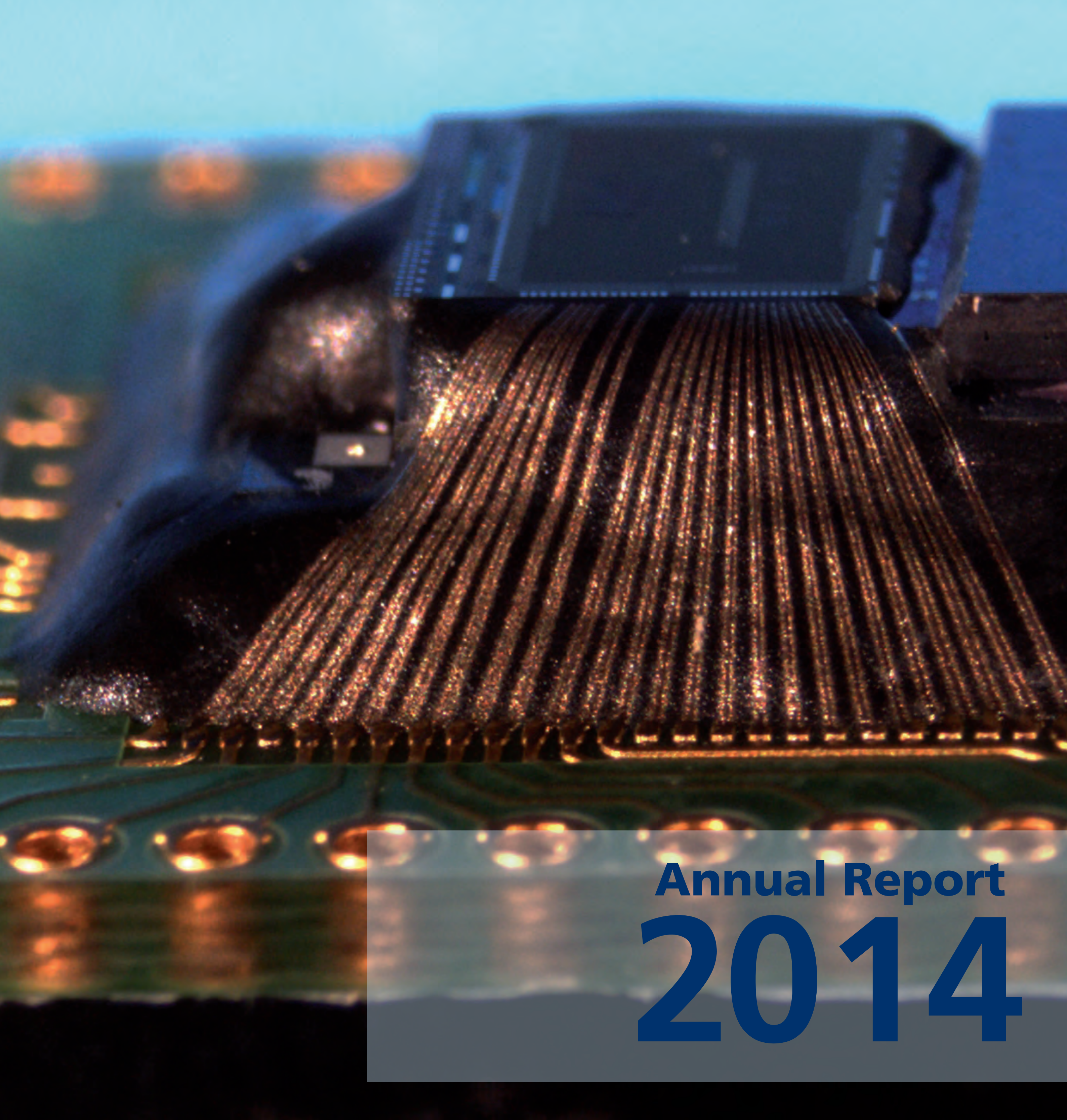
FRAUNHOFER INSTITUTE FOR ELECTRONIC NANO SYSTEMS ENAS



Annual Report 2014

A 3D integrated system in a package (SiP) "CoolPod" is assembled by triple stacking of three devices (ASIC, acceleration sensor, Powerdown interrupt generator) onto customized printed circuit board (PCB). Printed non planar silver nanoparticle-based chip-2-board interconnects are fabricated using Aerosol Jet technology and silver nanoparticle ink. Line width of printed interconnects was set to 25 µm.

Ein 3D-integriertes System in a Package (SiP) wurde mittels Dreifachstapel bestehend aus drei Bauelementen (ASIC, Beschleunigungssensor, Power down interrupt generator) auf einer individuell angepassten Leiterplatte realisiert. Die Fertigung der gedruckten Chip-2-Board-Verbindungen erfolgte mittels Aerosol-Jet-Technologie und Silbernanopartikeltinte. Die Linienbreite der gedruckten Verbindungen beträgt 25 µm.

The work related to integration technologies of single and stacked components on PCB was partly supported by the European Union (EFRE) and by the Free State of Saxony, Germany, within the research project CoolPod funded by SAB-Foerderbank (100107775).

Europäische Union

Europa fördert Sachsen.

EFRE

Europäischer Fonds für
regionale Entwicklung

ANNUAL REPORT 2014

CONTENT

PREFACE

Dear friends and partners of the Fraunhofer Institute for Electronic Nanosystems ENAS,
dear readers,

As an institute in the Fraunhofer-Gesellschaft, we research and develop under the motto "On behalf of the future". A large portion of the research is generated from contracted research, i.e. in the framework of direct orders from industry and publicly-funded projects. The challenges in 2014 and the coming years consist of the fact that, on the one hand, there is a new European funding framework program and, on the other, the national and Saxonian framework conditions have changed. Fraunhofer ENAS therefore continues to strive for high industry revenues. We would like to thank our partners and customers for their trust and support.

Our main topics in the market are microsystems technology/smart systems and their applications on the one hand and semiconductor technology/microelectronics/nanoelectronics on the other. In the spring of 2014, Prof. Dr. Stefan E. Schulz was appointed by the Fraunhofer-Gesellschaft board of directors to the position of deputy director of the Fraunhofer Institute for Electronic Nanosystems ENAS for the second time and works alongside Prof. Thomas Otto. Prof. Schulz represents, in particular, the semiconductor technology/microelectronics/nanoelectronics department.

At the end of April, Prof. Bernd Michel, who was the director of the Micro Materials Center department for many years, passed on the baton to Prof. Sven Rzepka. We thank Prof. Michel for his constructive cooperation. Prof. Rzepka will continue the work and be available to you in the future as a competent contact partner in the field of reliability.

The international symposium on the topic of smart integrated systems took place in Chemnitz in August 2014. National and international scientists and experts from the industrial sector presented current developments from the fields of microelectronics, microsystems technology and intelligent systems. In November 2014, in cooperation with our partners in Sendai, we organized the 10th Fraunhofer symposium on the topic of "Intelligent Systems for a Secure World".

With our annual review of 2014, we would like to provide you with insights into selected projects at the institute. You will find a cross-section of the wide range of activities at the institute in which smart systems are in the forefront. I invite you to ponder and think ahead. As a facility of the Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V., research and development for industrial applications is also one of our central concerns in 2015.

Director of the Fraunhofer Institute for Electronic Nano Systems ENAS

Prof. Dr. Thomas Gessner

VORWORT

Liebe Freunde und Partner des Fraunhofer-Instituts für Elektronische Nanosysteme ENAS,
sehr geehrte Leserinnen und Leser,

„Im Auftrag der Zukunft", unter diesem Motto forschen und entwickeln wir als Institut der Fraunhofer-Gesellschaft. Ein Großteil unseres Forschungsvolumens wird durch Vertragsforschung, d.h. im Rahmen von Direktaufträgen der Industrie und durch öffentlich geförderte Projekte, generiert. Die Herausforderungen in 2014 und den folgenden Jahren bestehen darin, dass einerseits ein neues Europäisches Förderrahmenprogramm existiert, sich andererseits auch die nationalen und sächsischen Rahmenbedingungen geändert haben. Fraunhofer ENAS strebt deshalb weiterhin einen hohen Industrieertrag an. Wir möchten an dieser Stelle unseren Partnern und Kunden für das Vertrauen und die Unterstützung danken.

Unsere Schwerpunktthemen am Markt sind die Mikrosystemtechnik/Smart Systems sowie deren Anwendungen auf der einen Seite und die Halbleitertechnologie/Mikroelektronik/Nanoelektronik auf der anderen Seite. Im Frühjahr 2014 wurde Prof. Dr. Stefan E. Schulz durch den Vorstand der Fraunhofer-Gesellschaft zum stellvertretenden Institutsleiter des Fraunhofer-Instituts für Elektronische Nanosysteme ENAS neben Prof. Thomas Otto bestellt. Prof. Schulz vertritt insbesondere den Bereich Halbleitertechnologie/Mikroelektronik/Nanoelektronik.

Ende April übergab der langjährige Abteilungsleiter des Micro Materials Centers Prof. Bernd Michel den Staffelstab an Prof. Sven Rzepka. Wir danken Prof. Michel für konstruktive Zusammenarbeit. Prof. Rzepka wird die Arbeiten kontinuierlich fortführen und Ihnen in Zukunft als kompetenter Ansprechpartner auf dem Gebiet Zuverlässigkeit zur Verfügung stehen.

Im August 2014 fand das internationale Symposium zum Thema Smart Integrated Systems in Chemnitz statt. Nationale und internationale Wissenschaftler und Experten aus der Industrie stellten aktuelle Entwicklungen auf den Gebieten Mikroelektronik, Mikrosystemtechnik und intelligente Systeme vor. Im November 2014 organisierten wir gemeinsam mit unseren Partnern in Sendai das 10. Fraunhofer Symposium zum Thema „Intelligente Systeme für eine sichere Welt".

Mit unserem Jahresrückblick 2014 möchten wir Ihnen einen Einblick in ausgewählte Projekte am Institut gewähren. Sie finden einen Querschnitt durch vielfältige Aktivitäten des Instituts, bei denen Smart Systems im Vordergrund stehen. Ich lade Sie zum Nach- und Vorausdenken ein. Als Einrichtung der Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. ist auch 2015 Forschung und Entwicklung für industrielle Anwendungen unser zentrales Anliegen.

Der Leiter des Fraunhofer-Instituts für Elektronische Nanosysteme ENAS

Prof. Dr. Thomas Geßner

@ Dirk Hanus

FRAUNHOFER ENAS

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The particular strength of the Fraunhofer Institute for Electronic Nano Systems ENAS lies in the development of smart integrated systems for different applications. Such systems combine electronic components with nano and micro sensors as well as actuators and communication units. Fraunhofer ENAS develops single components, technologies for their manufacturing as well as system concepts and system integration technologies and transfers them into production. That means, the institute offers research and development services from the idea, via design and technology development or realization based on established technologies to tested prototypes. If standard components do not meet the requirements, Fraunhofer ENAS provides prompt help in the realization of innovative and marketable products.

The product and service portfolio of Fraunhofer ENAS covers high-precision sensors for industrial applications, sensor and actuator systems with control units and evaluation electronics, printed functionalities like antennas and batteries as well as material and reliability research for microelectronics and microsystem technology. The development, the design and the test of MEMS/NEMS, methods and technologies for their encapsulation and integration with electronics as well as metallization and interconnect systems for micro and nanoelectronics and 3D integration are especially in the focus of the work. Special attention is paid to security and reliability of components and systems. Application areas are semiconductor industry, medical engineering, mechanical engineering, security sector, automotive industry, logistics as well as aeronautics.

With the working field smart systems integration Fraunhofer ENAS is able to support strongly the research and development of many small and medium sized companies as well as large scale industry. By integration of smart systems in different applications Fraunhofer ENAS addresses the above mentioned branches.

In order to focus the activities and to ensure a longterm scientific and economic success Fraunhofer ENAS has defined the three business units: Micro and Nano Systems, Micro and Nano Electronics / Back-End of Line as well as Green and Wireless Systems. They address different markets, different customers and moreover different stages of the value added chain depending on the required research and development services.

From an organizational point of view Fraunhofer ENAS is subdivided into the departments Multi Device Integration, Micro Materials Center, Printed Functionalities, Back-End of Line, System Packaging, Advanced System Engineering and Administration. The headquarters of Fraunhofer ENAS is located in Chemnitz. The department Advanced System Engineering is working in Paderborn. The department Micro Materials Center has a project group working in Berlin-Adlershof.

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Die besondere Stärke des Fraunhofer-Instituts für Elektronische Nanosysteme ENAS liegt in der Entwicklung von Smart Systems - sogenannten intelligenten Systemen für verschiedenartige Anwendungen. Die Systeme verbinden Elektronikkomponenten, Mikro- und Nanosensoren und -aktoren mit Schnittstellen zur Kommunikation. Fraunhofer ENAS entwickelt Einzelkomponenten, die Technologien für deren Fertigung aber auch Systemkonzepte und Systemintegrationstechnologien und überführt sie in die praktische Nutzung. D.h. Fraunhofer ENAS begleitet Kundenprojekte von der Idee über den Entwurf, die Technologieentwicklung oder Umsetzung anhand bestehender Technologien bis hin zum getesteten Prototyp. Wenn Standardkomponenten den Anforderungen nicht gerecht werden oder an Grenzen stoßen, versucht das Fraunhofer ENAS eine kundenspezifische Lösung zu finden.

Die Produkt- und Dienstleistungspalette von Fraunhofer ENAS reicht von hochgenauen Sensoren für die Industrie, Sensor- und Aktuatorsystemen mit Ansteuer- und Auswerteelektronik, über gedruckte Funktionalitäten wie Antennen oder Batterien bis hin zur Material- und Zuverlässigkeitsforschung für die Mikroelektronik und Mikrosystemtechnik. Im Fokus stehen die Entwicklung, das Design und der Test von siliziumbasierten und polymerbasierten MEMS und NEMS, Methoden und Technologien zur deren Verkappung und Integration mit Elektronik sowie Metallisierungs- und Interconnectsysteme für die Mikro- und Nanoelektronik und die 3D-Integration. Spezielles Augenmerk wird auf die Sicherheit und Zuverlässigkeit der Komponenten und Systeme gerichtet. Die Anwendungsfelder sind die Halbleiterindustrie, die Luft- und Raumfahrt, der Automobilbau, die Sicherheitsbranche, die Logistik, die Medizin- und Prozesstechnik sowie der Maschinenbau.

Mit der Ausrichtung auf die Smart Systems Integration ist das Fraunhofer ENAS in der Lage, die Forschung und Entwicklung sowohl von KMUs als auch von Großkonzernen zu unterstützen. Durch die Integration intelligenter Systeme in die verschiedenartigsten Anwendungen adressiert Fraunhofer ENAS die oben aufgeführten Branchen.

Um die Aktivitäten des Fraunhofer ENAS zu fokussieren, wurden die Schwerpunkte im Technologieportfolio und in der Marktbearbeitung auf die drei Geschäftsfelder Micro and Nano Systems, Micro and Nano Electronics / Back-End of Line sowie Green and Wireless Systems gelegt. Jedes Geschäftsfeld verfügt über ein eigenes Kundenprofil, das in Abhängigkeit der benötigten Forschungs- und Entwicklungsleistungen verschiedene Stellen der industriellen Wertschöpfungsketten anspricht.

Organisatorisch ist Fraunhofer ENAS in die sechs Fachabteilungen Multi Device Integration, Micro Materials Center, Printed Functionalities, Back-End of Line, System Packaging und Advanced System Engineering sowie die Verwaltung gegliedert. Der Hauptstandort des Fraunhofer ENAS ist Chemnitz. Die Abteilung Advanced System Engineering ist in Paderborn angesiedelt. Die Abteilung Micro Materials Center hat eine Projektgruppe in Berlin-Adlershof.

DEPARTMENT
MULTI DEVICE INTEGRATION

The strategic direction of the Multi Device Integration department is focused on the integration of MEMS and NEMS into functional modules and the development of MEMS and NEMS using silicon-based and nonsilicon materials (nanocomposites, ceramics and polymers).

MEMS/NEMS design and development

Novel modeling and simulation techniques are essential for designing micro and nano electro-mechanical systems. Coupled field analyses enable accurate predictions of MEMS and NEMS functional components and devices behavior. In consideration of process-induced geometric tolerances, the whole simulation chain is feasible. This includes the layout, process emulation, behavioral modeling of components with the help of the Finite Element Method and model order reduction up to system design.

Microoptics

The Fraunhofer ENAS develops microsystem-based optomechanical setups and packages using a parameterized design, including thermal and mechanical simulations. Examples for the activities in the field of microoptics are the development and validation of infrared MEMS spectrometers and chemical sensors. Such systems can be configured for different wavelength bands and hence be used in various applications. Food studies, environmental, condition and process monitoring, medical diagnostics, metrology or the physical forensic analysis belong to the fields of application.

Fluidic integration and system technologies

Microfluidics has become an important tool for many applications, e.g. in the fields of medical diagnostics, health care, food and environmental monitoring, chemical processing and consumer products. Microfluidic systems enable faster analyses, lower sample and reagent volumes, new methods of detection, advanced cooling mechanisms and the processing of macroscopically difficult to control chemical reactions. The integration of additional functionality into such microfluidic systems leads to smart, autonomous devices, reduces fluidic interfaces and requires less complex control and readout instrumentation.

Measurement, test and characterization

A method for the extremely fast determination of dimensional and material parameters based on a combination of the Finite Element Method (FEM) and the measurement of eigenfrequencies has been developed in recent years and is now improved and adapted to different classes of MEMS devices. In fabrication sequence, the eigenfrequencies are measured by optical vibration detection and electrostatic excitation of the sample by external optical transparent electrodes. A further step calculates the dimensions or material parameters by estimation algorithms, being performed in less than two seconds and at wafer-level.

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DEPARTMENT
MICRO MATERIALS CENTER

Founded by Prof. Bernd Michel, the Micro Materials Center at today's Fraunhofer ENAS has some 20 years of experience in research and services dedicated to functional safety and reliability of microelectronics and smart systems. Best in class numerical simulation seamlessly combined with innovative experimental analyses are employed to let novel ideas on smart systems architectures and technologies become real industrial products. Other than research demonstrators, sellable products need to provide their full functionality safely and robustly for the entire lifetime promised to the customer – under all operational and environmental conditions they are specified for. Design for reliability by virtual prototyping based on physics of failure strategies is the path to reach this goal in minimum time. The Micro Materials Center has been developing the tools and schemes required for the implementation of this strategy into industrial practice. This has been done in close cooperation with our partners from all major companies in the field of smart systems technology. We are continuously widening the field of coverage and the accuracy of the reliability methodology developed.

Competences

- Microreliability and nanoreliability of components, systems and complete applications
- Thermo-(electro-)mechanical reliability analysis
- Crack avoidance strategies
- Reliability for avionics and space applications (JTI Clean Sky, ESA Projects etc.)
- Microreliability for electronics and smart sensor systems in fully electrical but also in hybride and ICE vehicles; reliability and safety of systems for autonomous driving
- Solder reliability for micro nano interconnects
- Reliability for packaging in the micro/nano integration field
- Reliability for nanoelectronics and smart systems (3D integration, More than Moore)
- Physics of failure analysis, fatigue and creep analysis
- Accelerated stress testing strategies (e.g. combined tests: multiple loads simultaneously)
- Design for manufacturability and reliability based on numerical methods fully calibrated and validated
- Virtual prototyping for minimum time-to-market in smart system product development
- Local deformation analysis (microDAC, nanoDAC, fibDAC, nanotom, Raman, EBSD, X-ray etc.)
- Analysis of internal stresses with highest spacial resolution (in MEMS, thin film stacks, BEOL structures etc.)

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DEPARTMENT PRINTED FUNCTIONALITIES

The department Printed Functionalities focuses on printing technologies for the manufacturing of printed products which do not solely address the human visual sense but employ these deposition technologies for the application of functional materials. These printed functionalities range from simple conductivity, semi conductivity and isolation up to chemical activity e.g. in batteries or catalysis. These functionalities can improve and enhance the performance and the architecture of smart systems e.g. by printed interconnections or printed power modules. In future thus equipped products will have functionalities beyond color, enabling them to perceive their neighborhood and their own state, allow the interaction with a user and the communication with computer networks, in short: convey them to an intelligent item of the internet of things.

In our understanding the term "Printed Functionality" goes far beyond color and we envision that the functionalities electrical conductivity, adapted dielectric properties, electrical semi-conductivity, electric power, electro-luminescence / light emission, sensing environment, surface protection, intelligence via chip or even catalysis will be manufactured by employing press and post-press technologies. And we expect that the digital printing technology inkjet will contribute substantially by enabling the deposition of very small amounts of expensive functional materials.

Our equipment enables us to deposit and process various types of materials in form of inks. We have the machinery available to scale-up inkjet printing from single nozzle deposition in flatbed mode to industrial level in web-fed systems. This enables us to go for Digital Fabrication generally. For thicker layers and higher throughput we employ screen and/or gravure printing – both in flatbed or web-fed mode. For sophisticated postpress treatment we have a Novacentrix® PulseForge® installed in a web-fed system.

Additionally we focus in our research on the customization of printed batteries to power appropriate applications and we excel in the design, development, manufacturing and characterization of printed antenna systems.

All activities are carried out in close cooperation with the Technische Universität Chemnitz and industrial partners.

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DEPARTMENT BACK-END OF LINE

The department Back-End of Line focuses on

- Materials and process development
- Process integration
- Modeling and simulation

for interconnect systems in ultra large-scale integrated CMOS devices (ULSI) as well as MEMS and NEMS components.
Special emphasis is placed on integrating low-k, porous ultra low-k materials and airgaps into copper damascene interconnect systems. Adapted etching and cleaning techniques, k-restore processes after patterning, diffusion barrier and copper CMP processes and barrier compatibility are investigated.
New architectures for interconnect and nanosystems are under investigation with respect to the integration of carbon nanotubes. Development and optimization of the complete technology are accompanied by electrical characterization and modeling / simulation of carbon nanotube containing systems.
The development of a new generation of 2D / 3D magnetic field sensors includes tailored processes for XMR layer deposition, geometric and magnetic micro-patterning as well as electromagnetic sample characterization.
3D and system integration require metallization solutions for redistribution layers, specific wafer bonding techniques and for high aspect ratio "through silicon vias" (TSVs). PVD, CVD and ALD barrier and seed layers, copper CVD and electroplating (ECD) are provided to address different feature geometries and various applications. For wafer thinning of different substrate materials, processing solutions are developed using grinding, spin etching and CMP.
Furthermore, advanced models and simulation tools for PVD, CVD and ALD processes as well as for interconnect and nano systems are developed.

Competences and research fields

The main competences and research fields of the department BEOL are in the fields of:

- Integration of low-k and ultra low-k (ULK) dielectrics and airgaps
- Metallization for micro and nanoelectronics as well as for 3D and system integration
- Process and equipment modeling and simulation
- Modeling and simulation of interconnect and nano systems
- Planarization and surface modification for BEOL and MEMS / NEMS fabrication
- Wafer-level integration of carbon nanotubes for interconnects, CNT-FETs and sensors
- Magnetoresistive sensors based on spin-valve systems

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Back-End of Line:

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DEPARTMENT
SYSTEM PACKAGING

The department System Packaging is working in the field of packaging technologies for MEMS and NEMS covering topics from zero-level packaging up to multi-level packaging. The potentials of packaging and system integration are manifold, ranging from hybrid integration of components on application-specific substrate carriers, over monolithic integration of electronic, sensing and actuating components on substrate. In addition to the increasing functionality and reliability, the miniaturization and the smart systems integration are the greatest challenges for 'More-than-Moore' development.

Besides conventional wafer bonding techniques such as silicon direct bonding, anodic, eutectic, adhesive, and glass frit bonding, new technologies such as laser assisted bonding, reactive bonding as well as low-temperature and thermo-compression bonding are researched and adapted for special application areas. Furthermore, the competence of the department involves dicing, chip and wire bonding as well as thin wafer handling. A new approach for the department is the medical use of packaged micro devices. Therefore, MEMS packaging techniques and thin film encapsulation technologies are investigated and characterized in terms of hermetical and biocompatible properties. New application fields for nano patterns realized by nano-imprint lithography and pattern transfer are e. g. optics, electronics and medical technology.

The department System Packaging analyzes nano scale intermediate layers and layer systems using PLD, PVD and Aerosol Jet deposition for advanced MEMS packaging solutions. The aim of these new bond process investigations is to achieve a permanent and hermetic sealed joint between two wafers, using the lowest process temperature possible. Another application of nano structures are micro energy storage systems. By combining nanostructured electrodes with ionic conductors, electric double-layers with large volumetric capacitance are realized resulting in autonomous micro systems such as smart sensor networks and medical implants.

Furthermore, the department is focusing on acoustic applications including capacitive micromachined ultrasonic transducers (CMUT), speakers and microphones fabricated by using MEMS technologies. Using amorphous metals, free standing membranes with superior mechanical properties like high strength and elastic limit are realized using PVD technologies. In combination with printed magnets based on screen printing paste filled with magnetic particles and electrochemically deposited coils, electrodynamic actuators are realized.

Competences

- MEMS packaging, wafer-level packaging and 3D integration
- Nanoscale effects and imprinting
- Aerosol Jet and screen printing
- Medical and acoustic applications

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DEPARTMENT
ADVANDCED SYSTEM ENGINEERING

The department Advanced System Engineering (ASE) focuses on developing simulation methods for heterogeneous micro and nano electronic systems as well as for specific wireless devices such as RFID-systems. The goal of all these activities – lead in close collaboration with the University of Paderborn – is the characterization and optimization of complex electronic systems in order to assess their electromagnetic reliability as well as the signal and clock integrity at high frequencies at the IC level, for packages, modules and PCB. This research provides a crucial contribution to the development of reliable miniaturized systems.

Not all parasitic and coupling effects of complex high density systems can be predicted with the help of EDA tools and the associated simulation approaches during the design phase. Therefore, it is very helpful for the system designer to have the possibility to visualize the EM-field of first prototypes with the help of the new 3D near-field scanning technology developed by Fraunhofer ENAS department ASE. This technology provides a powerful methodology allowing the precise detection of coupling paths and the characterization of antenna patterns (e.g. RFID design) and facilitates the efficient design procedure.

Another innovative concept developed by the department ASE – serving the philosophy of smart wireless systems – is the SUPA technology which enables the wireless transmission of data and energy up to 50 W. With this technology, surfaces of furniture or interior of automobiles and airplanes can supply power and data wirelessly to any electronic equipment. A novel sending antenna matrix, placed inside the energy transmitting surface and detecting automatically the receiver's position, enables a focused and restricted transmission magnetic field. This smart switching system contributes to dramatically limit and localize the generated fields, reducing the potential interferences with other systems.

Competences

Main competences and long-term experiences are:

- Wireless energy transmission
- Mobile wireless and RFID smart sensor systems for harsh environments
- Advanced modeling and analysis of EMC and SI-effects
- System modeling and simulation
- Model-based development methods for custom specific heterogeneous systems
- Advanced 3D near-field scanning (high resolution up to 6 GHz)
- RF and EMC measurement on wafer-level up to 20 GHz
- Multiphysical modeling and simulation using CST µWave Studio, AnSys (HFSS) and Cadence (HSPICE/Spectra)

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ADVISORY BOARD

The advisory board is an external advisory body attached to the institute and consists of representatives of science, industry, business and public life. The members of the advisory board are appointed by the Executive Board of Fraunhofer-Gesellschaft with the approval of the director of the institute. Their annual meetings are attended by at least one member of the Executive Board.

Fraunhofer ENAS thanks our former advisory board member RD Dr. Ulrich Katenkamp from the Federal Ministry for Education and Research for accompanying the institute for five years. The institute welcomes the new board member Jürgen Berger. He is division director of Electronic and Micro Systems in the VDI/VDE Innovation + Technik GmbH.

In 2014, the members of the Fraunhofer ENAS advisory board were:

Chairman:
Prof. Dr. Udo Bechtloff, CEO, KSG Leiterplatten GmbH

Deputy chairman:
Prof. Dr. Hans-Jörg Fecht, Director of the Institute of Micro and Nanomaterials, Ulm University

Members of the advisory board:
MRn Dr. Annerose Beck, Saxon State Ministry of Sciene and Art
Jürgen Berger, Division Director Electronic and Micro Systems, VDI/VDE Innovation + Technik GmbH
Dr. Wolfgang Buchholtz, Manager Project Coordination, GLOBALFOUNDRIES
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Dr. Christiane Gottschalk, CTO, ASTeX GmbH
Dr. Arbogast M. Grunau, Director Product Development, Schaeffler KG
MDgin Barbara Meyer, Saxon State Ministry of Economy, Technology and Transportation
Prof. Dr. Ulrich Schubert, School of Chemistry and Earth Sciences, Jena University
Uwe Schwarz, Manager Development MEMS Technologies, X-FAB Semiconductor Foundries
Dr. Markus Ulm, Department Manager Engineering Advanced Concepts, Robert Bosch GmbH
Prof. Dr. Arnold van Zyl, Rector, Technische Universität Chemnitz
Helmut Warnecke, CEO, Infineon Technologies Dresden GmbH & Co. OHG

Fraunhofer ENAS thanks the advisory board for supporting our institute.

FACTS AND FIGURES

Development of the Fraunhofer ENAS / Entwicklung des Fraunhofer ENAS

	Year 2008	2009	2010	2011	2012	2013	2014
Operating budget (in million euros) / Betriebshaushalt (in Mio. €)	5.2	6.7	7.6	8.4	9.6	10.6	12.4
Increasing of the budget (related to 2008) / Steigerung des Haushalts (bezogen auf 2008)		29 %	46 %	62 %	85 %	104 %	138 %
Industrial revenues (in million euros) / Wirtschaftsertrag (in Mio. €)	3.4	3	2.8	2.8	3.49	4.1	5.2
Investment (in million euros) / Investitionen (in Mio. €)	0.65	5.45	6.8	1.5	1.81	1.44	7.23
Staff / Mitarbeiterinnen und Mitarbeiter	63	73	91	102	104	125	129
Apprentices / Auszubildende	0	2	3	5	6	7	7
Students and student assistants / Studenten und Hilfskräfte	10	10	20	40	43	51	51
Publications and oral presentations / Publikationen und Vorträge	61	75	114	119	112	215	198
Patents / Patente	7	5	13	20	8	17	9
Dissertations / Promotionen	6	0	4	2	3	3	3
Academic lectures / Vorlesungen (Technische Universität Chemnitz)	17	17	23	27	24	24	24
Academic lectures / Vorlesungen (Universität Paderborn)	8	9	9	8	9	8	7
Academic lectures / Vorlesungen (Technische Universität Dresden)	0	0	2	2	2	1	0

FACTS AND FIGURES

Financial situation

The year 2014 was affected by increase within all fields of Fraunhofer ENAS. Not only the increased budget but also the continued increasing third-party funds underline the sound development strategy of the institute. Within 2014, Fraunhofer ENAS reached increased external funds of 10.62 million euros. The revenues quota is again excellent with 86 percent. Contracts from German and international industry as well as trade associations reached just 5.2 million euros. This is 42.1 percent of the total operating budget of 12.4 million euros.

Fraunhofer ENAS invested 2.8 million euros in equipment investment as well as building activities. Additionally strategic invest of 0.38 million euros has been realized in 2014. Moreover, 4.05 million euros were invested for purchasing a nanolithography system funded by the Free State of Saxony and the Fraunhofer-Gesellschaft.

Head of Administration:
Gottfried Höppner
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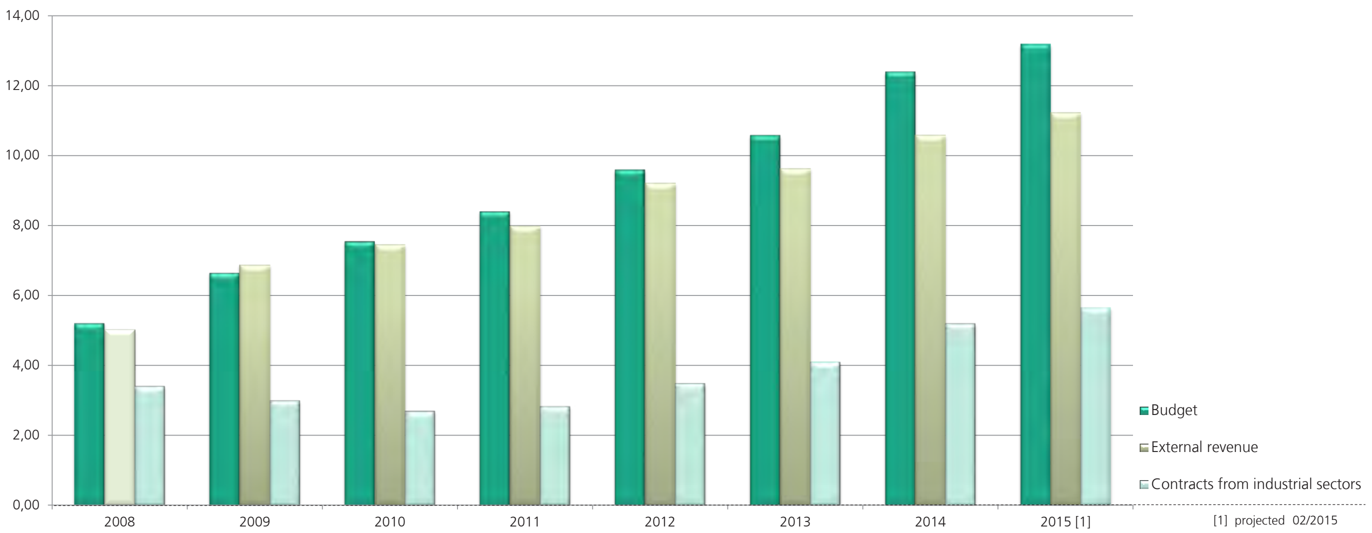
Human Resources

The institute's success is rooted in the minds of its employees and their knowledge of details and relationships, products, technologies and processes. Third time our own apprentices finished their vocational training successfully. In cooperation with the Technische Universität Chemnitz and the University of Paderborn students and young scientists have successfully defended their thesis. Some of them belong now to our staff.

Fourteen employees joined the team, bringing the total staff at Fraunhofer ENAS in Chemnitz, Paderborn and Berlin to 129 at the end of 2014. Seven employees left Fraunhofer ENAS in order to work now in industry or due to retirement. The majority of our staff are qualified scientists and engineers. Fraunhofer ENAS offers job training as micro technology technicians. Currently there are seven apprentices employed.

At the end of 2014 there were 51 interns, student assistants and students working on their Bachelor, Master or Diploma thesis employed. These regular team members belong to our source for coming new scientists and technicians.



Finanzielle Situation und Invest

2014 war für Fraunhofer ENAS ein von Wachstum in allen Bereichen geprägtes Jahr. Nicht nur das gestiegene Budget, sondern auch die weiter steigenden Drittmittelerträge unterstreichen die solide Entwicklungsstrategie unseres Institutes. In 2014 erreichte Fraunhofer ENAS externe Erträge in Höhe von 10,62 Millionen Euro. Die Ertragsquote liegt bei sehr guten 86 Prozent. Die Aufträge aus deutschen und internationalen Industrieunternehmen erreichten 5,2 Millionen Euro, was einem Industrieanteil von 42,1 % am Betriebshaushalt von 12,4 Millionen Euro entspricht.

Die eigenen Geräteinvestitionen und Investitionen in die Ausstattung/Bau des Gebäudes im vergangenen Jahr betrugen 2,8 Millionen Euro. Der strategische Invest in 2014 betrug 0,38 Millionen Euro. Darüber hinaus wurden aus Mitteln des Landes Sachsen und der Fraunhofer Gesellschaft 4,05 Millionen Euro für den Erwerb eines Nanolithografiesystems investiert.

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Personalentwicklung

Der Erfolg eines jeden Unternehmens und auch jeder Forschungseinrichtung steckt in den Köpfen der Beschäftigten, ihrem Wissen über Details und Zusammenhänge, Produkte, Technologien und Verfahren. 2014 schloss unser dritter Jahrgang Azubis erfolgreich die Ausbildung ab. In Kooperation mit der TU Chemnitz und der Universität Paderborn haben Studentinnen und Studenten sowie junge Wissenschaftlerinnen und Wissenschaftler ihre Graduierungsarbeiten erfolgreich verteidigt. Einige von ihnen verstärken jetzt unser Team.

Es wurden vierzehn Mitarbeiterinnen und Mitarbeiter eingestellt, sodass zum Ende 2014 129 Personen an den Fraunhofer ENAS Standorten Chemnitz, Paderborn und Berlin beschäftigt waren. Sieben Mitarbeiterinnen und Mitarbeiter wechselten von Fraunhofer ENAS entweder in die Industrie oder in den Ruhestand. Fraunhofer ENAS bildet seit 2009 Mikrotechnologen aus. Zurzeit befinden sich sieben Mikrotechnologen in der Ausbildung.

Ende 2014 waren darüber hinaus 51 Praktikanten, Diplomanden/Masterstudenten und studentische Hilfskräfte bei Fraunhofer ENAS beschäftigt. Dieser Mitarbeiterstamm erweist sich in wachsendem Maße als Quelle für den Nachwuchs von Wissenschaftlern und Technikern.

FRAUNHOFER ENAS
– PARTNER FOR INNOVATION

Product and service portfolio

- High-precision sensors for industrial applications
- Sensor and actuator systems with control units and evaluation electronics
- Printed functionalities like antennas and batteries
- Material and reliability research for microelectronics and microsystem technology
- Development, design and test of MEMS/NEMS
- Simulation and modeling of devices, processes and equipment for micro and nanosystems
- Integration of nanofunctionalities, such as carbon nanotubes, quantum dots
- Methods and technologies for MEMS/NEMS encapsulation and integration with electronics
- Metallization and interconnect systems for micro and nanoelectronics and 3D integration
- Reliability of components and systems
- Analytics for materials, processes and devices

Application fields

- Semiconductor and semiconductor equipment and materials industries
- Communication sector
- Medical engineering
- Mechanical engineering
- Security sector
- Automotive industry
- Logistics
- Aeronautics

The institute offers research and development services from the idea, via design and technology development or realization based on established technologies to tested prototypes.
If standard components do not meet the requirements, Fraunhofer ENAS provides prompt help in the realization of innovative and marketable products.

Interdisciplinary cooperation – key of success

Fraunhofer ENAS is an active member of different worldwide, European and regional industry-driven networks, starting from Semi and MEMS Industry Group, via EPoSS – the European Technology Platform on Smart Systems Integration, Silicon Saxony and IVAM up to the Smart Systems Campus Chemnitz. The complete list is included in the attachment.
Nearly 14 percent of our revenue is generated by international cooperation projects.

Cooperation with industry

With the working field smart systems integration Fraunhofer ENAS is able to support strongly the research and development of many small and medium sized companies as well as large scale industry. By integration of smart systems in different applications Fraunhofer ENAS addresses the branches listed in the box.
Our most common way of cooperation with industry is contract research for an individual partner. If the tasks to be solved are too complex we offer pre-competitive research. In these cases, teaming up with companies and research institutes and public funding support is more effective than operating solo.
In 2014 Fraunhofer ENAS has cooperated with more than 150 partners from industry worldwide. Fraunhofer ENAS carries out direct research and development orders as well as practical joint projects and pre-competitive research.

Cooperation within the Smart Systems Campus Chemnitz

Smart Systems Campus Chemnitz is an innovative network with expertise in micro and nano technologies as well as in smart systems integration. This technology park provides renowned scientific and technical centers with entrepreneurial spirit and business acumen and an economic boost at a location where everything is on the spot. A close cooperation of science, applied research and industry is there an everyday reality and reflects a strategy that is being fulfilled. Main partners are the Technische Universität Chemnitz, the Fraunhofer ENAS, young companies within the start-up building and companies within the business park.

Cooperation with universities and research institutes

Fraunhofer ENAS has established a strategic network with research institutes and universities in Germany and worldwide.
Germany funds Excellence Initiatives for Cutting-Edge Research at Institutions of Higher Education. Fraunhofer ENAS works in two of these clusters of excellence, which have been accepted in June 2012.

- Merge Technologies for Multifunctional Lightweight Structures – MERGE of the Technische Universität Chemnitz
- Center for Advancing Electronics Dresden – cfaed of the Technische Universität Dresden

In Asia, long-term cooperation exists with the Tohoku University in Sendai, the Fudan University Shanghai and the Shanghai Jiao Tong University.
A very strong cooperation exists with the Technische Universität Chemnitz. This cooperation ensures synergies between the basic research conducted at the TU Chemnitz and the more application-oriented research at the Fraunhofer ENAS. The main cooperation partner at the Technische Universität Chemnitz is the Center for Microtechnologies. The cooperation results in a common use of equipment, facilities and infrastructure as well as in the cooperation in research projects. Printed functionalities and lightweight structures are topics of the cooperation with the faculty for Mechanical Engineering. The department Advanced System Engineering located in Paderborn continues the close cooperation with the University Paderborn especially in the field of electromagnetic reliability and compatibility as well as SUPA technology.

Main partners of basic research

- Technische Universität Chemnitz
- University Paderborn
- TU Dresden
- Tohoku University
- Fudan University
- Jiao Tong University

Cooperation within Fraunhofer-Gesellschaft

Fraunhofer ENAS belongs to the Fraunhofer Group for Microelectronics VµE since its foundation. Moreover, Fraunhofer ENAS is a member of the Fraunhofer Alliance Nanotechnology and the Fraunhofer AutoMOBILE Production Alliance.
Together with the other institutes of the Fraunhofer Group Microelectronics Fraunhofer ENAS participates in the Heterogeneous Technologies Alliance, which is a novel approach to creating and developing microtechnologies, nanoelectronics and smart systems for next-generation products and solutions together with CEA-Leti, CSEM and VTT.
Within the lighthouse project Theranostic Implants Fraunhofer ENAS is working together with 11 other Fraunhofer institutes on strategic objectives.

FRAUNHOFER-GESELLSCHAFT

www.fraunhofer.de

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 66 institutes and research units. The majority of the nearly 24,000 staff are qualified scientists and engineers, who work with an annual research budget of more than 2 billion euros. Of this sum, around 1.7 billion euros is generated through contract research. More than 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Almost 30 percent is contributed by the German federal and Länder 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 nonprofit organization that takes its name from Joseph von Fraunhofer (1787–1826), the illustrious Munich researcher, inventor and entrepreneur.

DIE FRAUNHOFER-GESELLSCHAFT

www.fraunhofer.de

Forschen für die Praxis ist die zentrale Aufgabe der Fraunhofer-Gesellschaft. Die 1949 gegründete Forschungsorganisation betreibt anwendungsorientierte Forschung zum Nutzen der Wirtschaft und zum Vorteil der Gesellschaft. Vertragspartner und Auftraggeber sind Industrie- und Dienstleistungsunternehmen sowie die öffentliche Hand.

Die Fraunhofer-Gesellschaft betreibt in Deutschland derzeit 66 Institute und Forschungseinrichtungen. Knapp 24 000 Mitarbeiterinnen und Mitarbeiter, überwiegend mit natur- oder ingenieurwissenschaftlicher Ausbildung, erarbeiten das jährliche Forschungsvolumen von mehr als 2 Milliarden Euro. Davon fallen rund 1,7 Milliarden Euro auf den Leistungsbereich Vertragsforschung. Über 70 Prozent dieses Leistungsbereichs erwirtschaftet die Fraunhofer-Gesellschaft mit Aufträgen aus der Industrie und mit öffentlich finanzierten Forschungsprojekten. Knapp 30 Prozent werden von Bund und Ländern als Grundfinanzierung beigesteuert, damit die Institute Problemlösungen entwickeln können, die erst in fünf oder zehn Jahren für Wirtschaft und Gesellschaft aktuell werden.

Internationale Kooperationen mit exzellenten Forschungspartnern und innovativen Unternehmen weltweit sorgen für einen direkten Zugang zu den wichtigsten gegenwärtigen und zukünftigen Wissenschafts- und Wirtschaftsräumen.

Mit ihrer klaren Ausrichtung auf die angewandte Forschung und ihrer Fokussierung auf zukunftsrelevante Schlüsseltechnologien spielt die Fraunhofer-Gesellschaft eine zentrale Rolle im Innovationsprozess Deutschlands und Europas. Die Wirkung der angewandten Forschung geht über den direkten Nutzen für die Kunden hinaus: Mit ihrer Forschungs- und Entwicklungsarbeit tragen die Fraunhofer-Institute zur Wettbewerbsfähigkeit der Region, Deutschlands und Europas bei. Sie fördern Innovationen, stärken die technologische Leistungsfähigkeit, verbessern die Akzeptanz moderner Technik und sorgen für Aus- und Weiterbildung des dringend benötigten wissenschaftlich-technischen Nachwuchses.

Ihren Mitarbeiterinnen und Mitarbeitern bietet die Fraunhofer-Gesellschaft die Möglichkeit zur fachlichen und persönlichen Entwicklung für anspruchsvolle Positionen in ihren Instituten, an Hochschulen, in Wirtschaft und Gesellschaft. Studierenden eröffnen sich aufgrund der praxisnahen Ausbildung und Erfahrung an Fraunhofer-Instituten hervorragende Einstiegs- und Entwicklungschancen in Unternehmen.

Namensgeber der als gemeinnützig anerkannten Fraunhofer-Gesellschaft ist der Münchner Gelehrte Joseph von Fraunhofer (1787–1826). Er war als Forscher, Erfinder und Unternehmer gleichermaßen erfolgreich.

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HIGHLIGHTS 2014

R&D AND PROJECT HIGHLIGHTS

Theranostic implants – a Fraunhofer lighthouse project

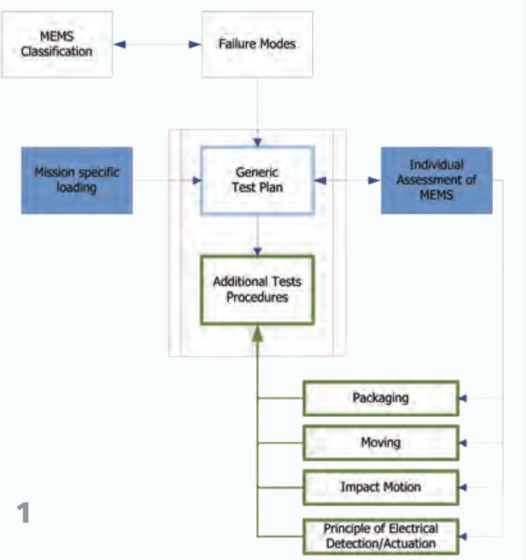
Theranostic implants are complex multi-functional implantable medical products that unite therapy and diagnostics into one medical system. Recording specific vital parameters is the diagnostic basis for the respectively introduced therapeutic measure, the effectiveness of which is optimized in a closed loop control. Due to the wide range of application possibilities, the constantly increasing quality requirements for highly specialized medical care and the demographic development, its significance is currently increasing greatly. Theranostic implants have thus gained an overall societal relevance which will lead to a jump in innovation in medical technology in the context of future technological possibilities. Such jumps in innovation result primarily from the interaction between several high-level technologies. Thus, on June 1, 2014, the lighthouse project “THERANOSTIC IMPLANTS” was initiated by the Fraunhofer-Gesellschaft and is intended to bundle the technological possibilities for developing implantable theranostic platforms.

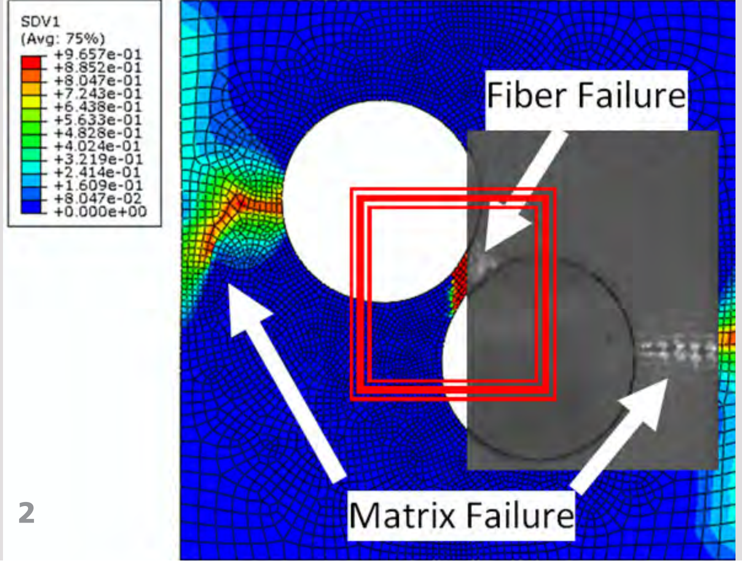
The objective is to take a leading position in the important key technologies for theranostic implants. In the framework of this lighthouse project, three demonstrators with a high relevance for the patients will be set-up and tested as examples.

In the framework of the project, 11 Fraunhofer institutes will develop one skeletal, one cardiovascular and one neuromuscular demonstrator. This will cover nearly the entire field of currently relevant theranostic implants. The technology platform developed in this manner establishes the conditions to quickly develop and manufacture modular medical components, systems and implants in the future.

In the framework of the project, the Fraunhofer ENAS will deal with sub-topics in the field of cardiovascular and neuromuscular demostrators with the development of a miniaturized inertial sensor, the approval-compliant packaging technologies of a multisensor system and its biocompatible encapsulation as well as the development of a micromachined energy storage device (SuperCap) which can supply the implant with power over a defined period of time.

Partners of the project are Fraunhofer IKTS, Fraunhofer FEP, Fraunhofer IPMS, Fraunhofer IAP, Fraunhofer IPT, Fraunhofer ENAS, Fraunhofer IBMT, Fraunhofer IIS, Fraunhofer IMS, Fraunhofer IWU, Fraunhofer IGB.





MEMS qualification and reliability assessment for space applications

1 Schematic MEMS testing approach for space applications.

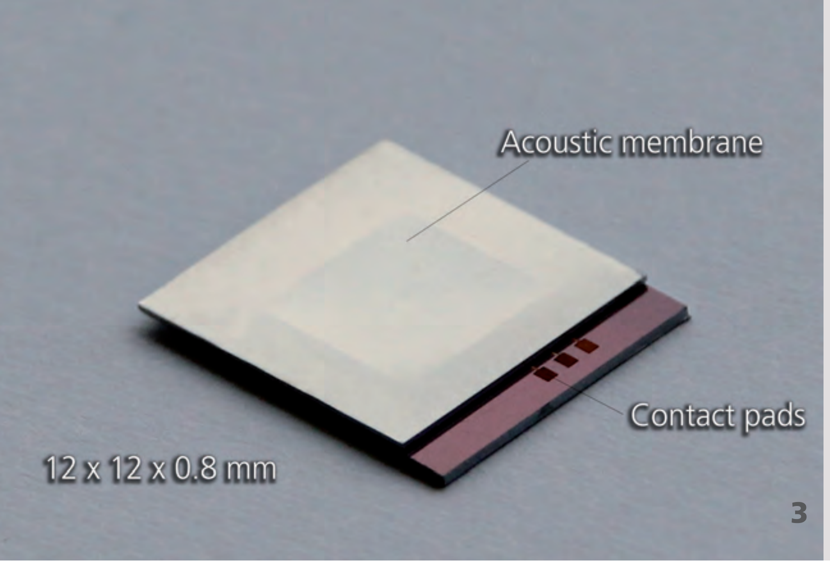
MEMS are considered to have a future large application potential for space missions as used for satellite communication and navigation as well as for different scientific purposes. Expected benefits are reduced device costs, size and mass, the latter leading to reduced mission payloads, besides reliability an essential criterion for device selection. A main obstacle of MEMS in space missions is the missing MEMS qualification and reliability assessment procedures and standards for space applications. Existing standards and testing guidelines for electronic devices have to be adapted and modified for MEMS devices. With this objective, project consortia of the Heterogeneous Technology Alliance with Fraunhofer ENAS (Chemnitz), CEA-LETI (Grenoble), CSEM (Neuchatel) and VTT (Finland) conduct respective research in different projects funded by the European Space Agency (ESA). The involved institutes prepare detailed MEMS testing strategies and protocols based on proven MEMS and failure classification schemes. The developed qualification and assessment procedures are demonstrated on a MEMS selection. In conclusion a final draft Technical Memorandum will be handed over to ESA.

Fatigue prediction of fiber reinforced polymers

2 Damaged fiber reinforced polymer sample exposed to tension load (FE analysis and experimental results).

An efficient scheme of virtual testing has been developed to significantly reduce experimental effort on determination of fatigue of FRP under various loading conditions. Effects of rate and temperature on strength and lifetime of structural polymer composites have been successfully determined utilizing enhanced simulation models of multi-ply composites together with the appropriate experimental inputs.

This topic has already concerned the aerospace industry during their fatigue tests of light structures but has also become of great relevance to applications in microelectronics and micro/nano system technologies in substrates and new innovative structural parts technologies following the More-than-Moore development strategy. In this sense, a new approach to accelerated testing has been assessed with respect to its potential for determining the fatigue behavior of composite materials exposed to complex and very challenging service conditions e.g., implantable biomedical, aeronautic or automotive applications. The modes of structural fatigue are analyzed and compared to the acceleration factors based on the visco-elastic time-temperature shift function. This way, the new method is clearly revealing its great potential for predicting the critical number of cycles to failure and its dependency on temperature and moisture as well as the long term fatigue strength of fiber reinforces polymers including complex electronic assemblies and smart systems and therefore allowing more precise lifetime estimation.



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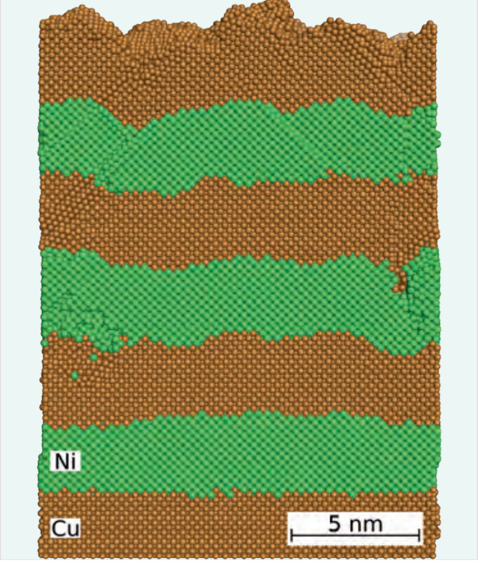

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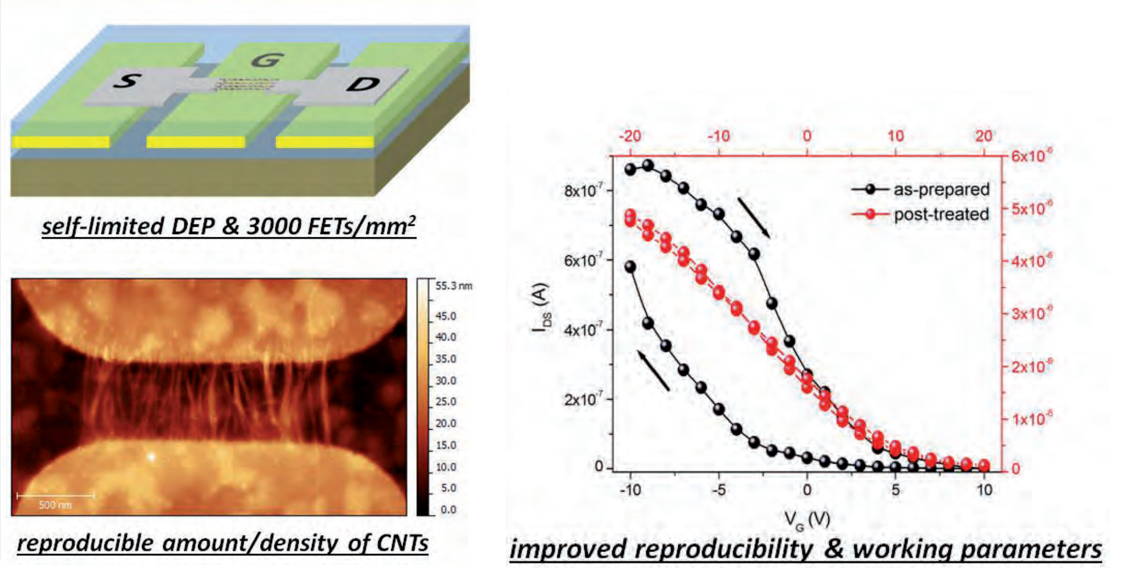


5

MEMS loudspeaker utilizing metallic glass membrane and deposited magnet

Micro loudspeakers are part of all mobile electronic devices in today's daily life such as cell phones, tablets and laptops. This market is estimated to demand more than one billion microspeakers per year and is still growing. With tendencies towards lower cost, thinner cases and higher energy efficiency of the mobile devices, also their components need to address these issues. In this respect, MEMS technology offers several advantages over conventional manufacturing like high accuracy and reproducibility, low-cost batch processing as well as new packaging possibilities (reflow soldering, electronics integration etc.).

At Fraunhofer ENAS, a silicon-based MEMS loudspeaker has been fabricated consisting of a metallic glass membrane with dispensed magnetic paste and electroplated micro coil. This represents the world's first approach of a MEMS speaker with electrodynamic actuation principle that is completely fabricated on wafer-level with no need to attach bulk magnets to the system manually. Due to their amorphous micro structure, metallic glasses exhibit superior mechanical properties including high strength, large elastic limit and no material fatigue. These properties make metallic glasses promising materials for movable MEMS structures as for example bars, suspension springs or membranes. To take advantage of this material in wafer-level fabrication, a thin film sputter deposition of metallic glasses has been established at Fraunhofer ENAS. This enables the integration of metallic glasses for various MEMS applications in the future.

3 *Fabricated MEMS loudspeaker chip.*

Parsivald – a new tool for the simulation of thin film growth

The new simulation tool Parsivald addresses the atomistic structure of thin functional films grown by vapor deposition. The acronym PARSIVALD stands for Parallel Atomistic Reaction Simulator for Vapor and Atomic Layer Deposition. Combining the efficiency of Kinetic Monte Carlo approaches with the atomistic accuracy of Molecular Dynamics, the new tool allows simulating the growth of comparably large nanostructures with dimensions of tens of nanometers (up to ~ 10^9 atoms). Most of the established thin film deposition schemes like PVD, CVD and ALD and deposition on nano structured substrates is covered by Parsivald. In combination with reactor scale process simulations and ab-initio simulations of material properties, Parsivald enables now the full predictive simulation cycle from the reactor conditions to the properties of the grown material. Parsivald is the outcome of the master project by Erik E. Lorenz which was performed in the device, process and equipment simulation group at the department BEOL.

4 *Atomistic model of PVD grown Cu-Ni-multilayers, as simulated by Parsivald.*

CMOS compatible integration of $BiFeO_3$

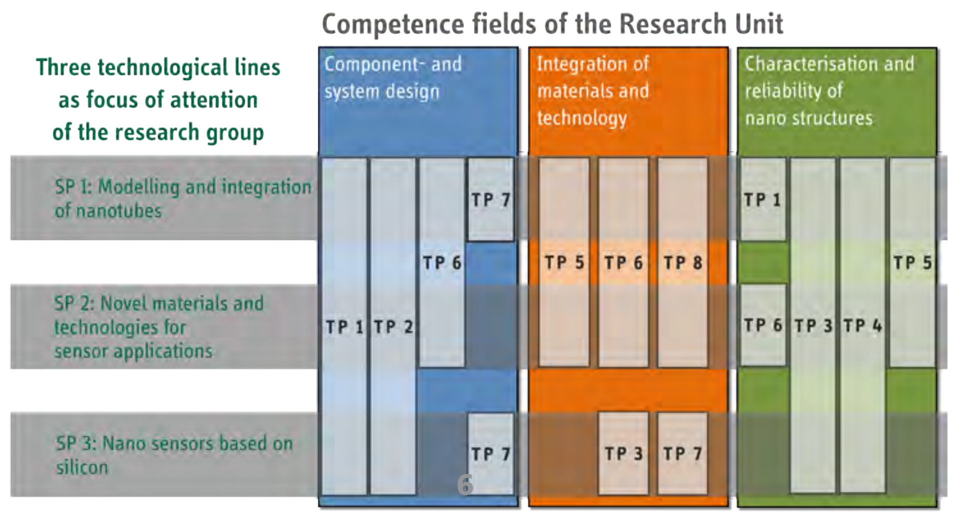
$BiFeO_3$ (BFO) belongs to the material class of multiferroics with coupled electric, magnetic and structural order parameters that yield simultaneous effects of ferroelectricity, ferromagnetism, and ferroelasticity in the same material. These materials offer a wide opportunity for potential applications in information storage, such as spintronic devices and sensors, where both electric and magnetic polarization can be coupled, giving enough opportunity for manipulating devices. However, there are challenges for CMOS compatible integration of this material because of its possible degradation.

In this project, performed together with the partners TU Chemnitz, HZDR Rossendorf and Fraunhofer FEP, Fraunhofer ENAS is responsible for the technology integration of the BFO material. The integration scheme includes electrode technology, etching technology and back-end technology. Typically, BFO like the other ferroelectric materials is very sensitive to plasma processes such as etching processes or deposition processes for dielectrics. Here, processes are optimized concerning low plasma power and preferably hydrogen free ambient.

Wafer-level integration of CNTs for high-frequency FETs

Within the cluster of excellence "Center for advancing electronics Dresden" (cfaed) distinct approaches (paths) are considered to improve and overcome the actual limitations of the semiconductor technology. Among them the "Carbon" path addresses the carbon materials as promising and suitable candidates to enable (develop) new technologies for electronic information processing. Here, nano objects like carbon nanotubes (CNTs) show great potential due their outstanding electrical properties like high mobility, capability to carry large current densities, resistance against electromigration, low capacitance etc. Moreover, the corresponding CNTs-based field effect transistors (CNT-FETs) are promising candidates for high-frequency front-end circuits in wireless communication systems due their potential for ballistic transport and the associated low noise, high power efficiency and high linearity. Aiming this goal, our team in Chemnitz has developed a new technology platform which allows a continuous fabrication of CNT-based FETs up to a wafer-level scale with a good control on CNT-density via employing a self-limited deposition process. Moreover, extended statistic studies on highly-dense CNT-FET arrays (3000 FETs/mm²) led to the establishment of a post-preparation treatment which enables a much better reproducibility as well as improved working parameters like better CNT-metal contact and reduced hysteresis.

5 *A schematic 3D sketch (left – top), a representative AFM image (left – bottom) and the corresponding transfer characteristics before and after post-treatment (right) of a CNT-based FET.*



6 *The subprojects of the DFG research unit according to the technological lines and their competence fields.*

Nano system integration network of competence – nanett

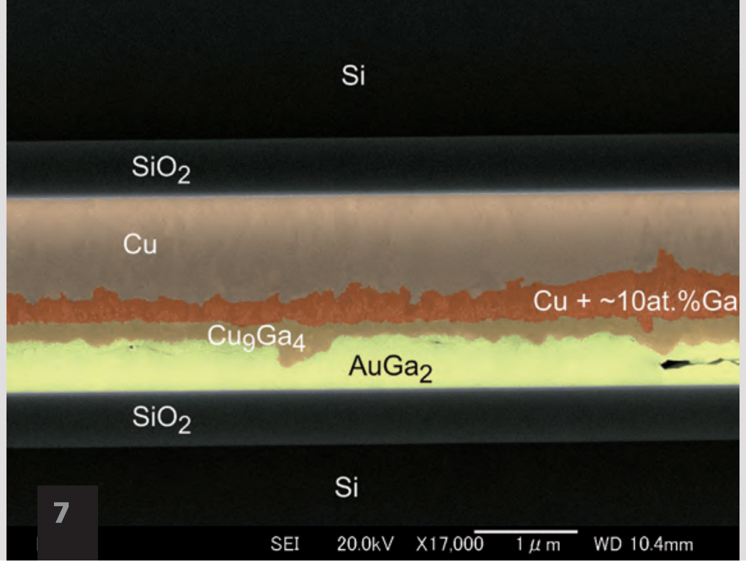
On October 22th 2014 the final status seminar was held within the 12th Symposium of Microsystem Technology in Chemnitz. After five years of collaborative research and development in the network of excellence the scientists of all the involved research institutes presented their final results. Partners from industry and science got an overview over the whole bandwidth of topics within the three flagship projects, which were presented by their project leaders Prof. Stefan Schulz, Dr. Steffen Kurth and Prof. Thomas Otto. Several talks of young researchers and an exhibition of the technology demonstrators gave the opportunity for deeper insights in the partial projects and the research work. Prof. Thomas Gessner, speaker of the network, thanked all the scientists for their outstanding performance over all the five years of project work. The tight collaboration between eight research institutes needs a lot of planning, coordination and communication. But at the end it was a great success. The nanett consortium was one of the successful initiatives within the program "Leading-edge Research and Innovation in the New German Länder" funded by the German Federal Ministry of Education and Research (BMBF).

DFG research unit 1713 "Sensoric Micro and Nano Systems"

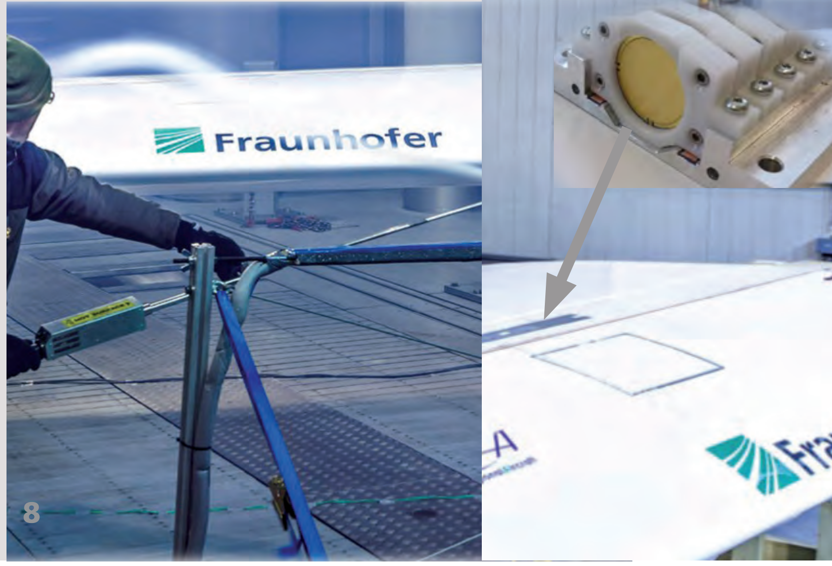
The research unit 1713 "Sensoric Micro and Nano Systems" was established by the German Research Foundation (DFG) in 2011 at the Technische Universität Chemnitz. In 2014, its continuation was successfully prolonged until 2017. Three partners – the Fraunhofer ENAS, Technische Universität Chemnitz, especially the Center for Microtechnologies, and the Leibniz IFW in Dresden – are joining their efforts to work on novel sensor principles in micro and nanoelectronics. The basis of this research is the interplay between classical microsensorics (e.g. MEMS structures, microfluidics) and nanosensorics (functionalized rolled-up tubes, carbon nanotubes). The scientific focus drives three main competence fields:

- Component and system design, which includes multiscale sensor modeling with novel approaches to incorporate quantum mechanical effects into classical sensor modeling.
- Material and technology integration, starting from the fabrication and functionalization of rolled-up smart tubes or carbon nanotubes and ending up in their heterogeneous integration in multifunctional sensor structures.
- Characterization and reliability investigations of nano structures including new, high resolution methods to characterize nano structures and their long-term stability.

www.zfm.tu-chemnitz.de/for1713/.



7 *SEM cross section showing an interface of silicon wafers bonded at 50 °C by gallium alloying.*



8 *Synthetic Jet Actuators integrated in an airplane wing during a wind channel test.*

Fraunhofer Project Center "NEMS/MEMS Devices and Manufacturing Technologies at Tohoku University" in Sendai, Japan

The Fraunhofer Project Center at Tohoku University (FPC at Tohoku University) is a platform for common research and development activities of Tohoku University and Fraunhofer Institute for Electronic Nano Systems ENAS. It was founded in 2012 as a result of long standing cooperation between Fraunhofer, City of Sendai and Tohoku University; it belongs to the World Premier International Research Centers Initiative Advanced Institute for Materials Research (WPI-AIMR). Under the guidance of Prof. Masayoshi Esashi, Director of Micro System Integration Center (µSIC), Prof. Thomas Gessner, Director Fraunhofer Institute for Electronic Nano Systems ENAS and Prof. Shuji Tanaka, Director Micro/Nano Education Center (MNC), scientists from Fraunhofer and Tohoku University jointly research on the application of novel materials for a diversity of micro systems. Furthermore, within the Project Center an active exchange between Germany and Japan of persons and ideas happens. Frequently researchers stay for several months at the founding institutions in Japan and Germany and conducting joint investigations. This fruitful collaboration already resulted in a number of interesting results and publications: characterization of sputtered metallic glass, investigation of thermal and electrical properties of nano wires, demonstration of micro system with amorphous actuator material and bonding of semiconductor substrates near room temperature by the help of gallium alloys. For example this particular technique allows joining of heterogeneous materials with electric conductive, hermetic tight interfaces that exhibit high mechanical strength.

CleanSky

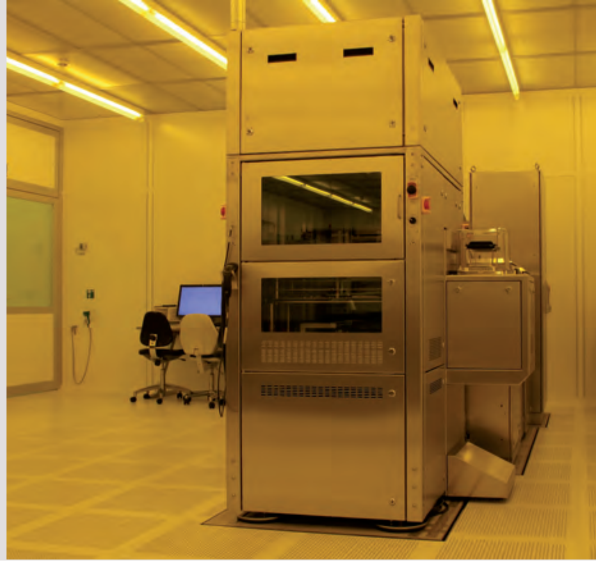
Until 2014, Fraunhofer ENAS was involved in activities within CleanSky and responsible for the development of different actuators for active flow control. This includes the fluidic actuators Synthetic Jet Actuators (SJA) and Pulsed Jet Actuators (PJA), as well as the mechanical system of the Smart Vortex Generator (Smart VG). There was further research and development on SJAs in 2014, which leads to a new generation of actuators. Nearly 100 of these actuators were tested under harsh environmental conditions in a climate wind tunnel tests. They survived temperatures of –7°C and artificial rain/ice rain without any failure. The wind speed was up to over 100 km/h. The results are a good starting point for the following developments on these actuators within further projects. For the actuator concept of PJAs, a performance improvement could be achieved this year. In the frame of the Integrated Active Components Demonstrator (IACD) a wind tunnel model of a 2½ D wing was successfully equipped with 180 single actuators and controlled by a special designed power electronics. This wind tunnel test was the first test, where such a number of Fraunhofer developed actuators was used.

International Research Training Group (IRTG) "Materials and Concepts for Advanced Interconnects and Nanosystems"

Together with Fudan University Shanghai, the Shanghai Jiao Tong University, the Fraunhofer Institute for Electronic Nano Systems ENAS Chemnitz, the Fraunhofer Institute for Microintegration and Reliability IZM and the Technische Universität Berlin, the Technische Universität Chemnitz works within the international graduate school "Materials and Concepts for Advanced Interconnects and Nanosystems". There are two faculties of TU Chemnitz involved, the faculty of Electrical Engineering and Information Technology with the Center for Microtechnologies and the faculty of Natural Sciences with the institutes of chemistry and the institute of physics. It is just a tradition to hold a summer school alternating in China and Germany. In 2014 the 9th summer school was held in Warnemuende.
There, the German PhD students discussed their research results together with the Chinese PhD students from Fudan University Shanghai. The Fudan University belongs to the top universities in China. At the summer school six PhD students from this university as well as their professors took part. The program of this workshop included additionally five invited presentations of top-class scientists. Professor Jana Zaumseil from the University Erlangen presented her scientific work in the field of novel transistors based on carbon nanotubes (CNT). Another highlight was the presentation of Dr. Ralf Prien from Leibniz Institute for Baltic Sea Research. He spoke about the application of sensors under extreme deep sea conditions. Prof. Gessner, the German speaker of the IRTG, explained: "This summer school is not only a week of very interesting science and research. Moreover, the summer school is an excellent possibility for PhD students to exchange ideas, to get new input for their work and for the successful completion of their doctoral thesis."
There are 16 German and 15 Chinese PhD students working within the International Research Training Group „Materials and Concepts for Advanced Interconnects and Nanosystems". The IRTG is funded by the German Research Foundation (DFG) of the Federal Republic of Germany and the Ministry of Education (MoE) of the People's Republic of China. After a successful evaluation in March 2010, the second period of the IRTG program started in October 2010, now extending the scientific topic to "Materials and Concepts for Advanced Interconnects and Nanosystems". The International Research Training Group will be funded until March 2015.

9 *Participants of the IRTG summer school 2014 in Warnemuende, Germany.*
photo © Piotr Mackowiak

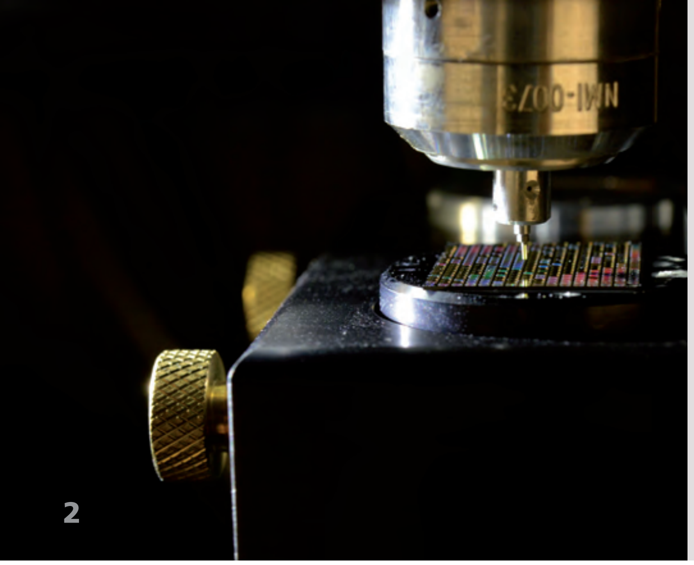
NEW EQUIPMENT

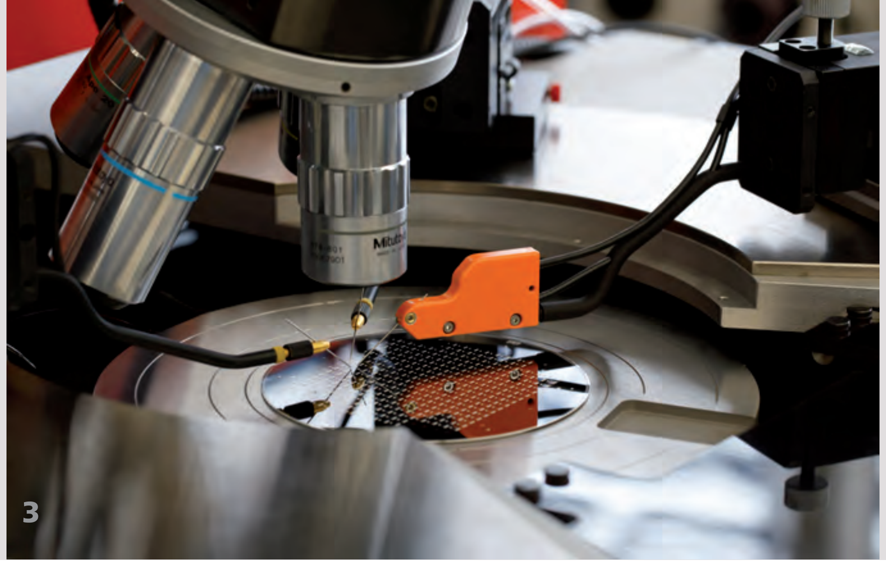


Electron beam lithography system

In 2014 Fraunhofer ENAS purchased a variable shaped electron beam lithography system (model ID: SB254) from Vistec Electron Beam GmbH for advanced research. The SB254 is a high-performance, cost-effective and universal electron beam lithography system, enabling the usage for both direct write and mask making for a large variety of applications in industry and applied research.
The system is capable of handling and exposing circular standard substrates (Si wafer with diameters of 100/150/200 mm with flat or notch) for semiconductor applications and nonstandard rectangular substrates which are used for mask making and optical applications. Equipped with 50 kV variable shaped beam electron optics, an address grid of 1 nm and an exposure platform with a stage travel range of 210 mm x 210 mm this system enables the exposure of isolated structures with critical dimensions below 20 nm. The e-beam system is controlled through a Graphical User Interface (GUI) which features fully automated cassette-to-cassette substrate handling, including substrate pre-alignment, electron optical column calibration and substrate height measurement. The high stage of automation allows for short exposure times, high availability and reduced costs of ownership. Additionally, a data preparation software package (ePlace) is included which is provided and maintained by EQUIcon Software GmbH. The system has been installed throughout September and October 2014 and became operational in December 2014.
The investment in the field of nanolithography at Fraunhofer ENAS also included a Jeol Scanning Electron Microscope JSM-7800F for optical characterization of mesoscopic structures and a resist track for standard and nonstandard substrate coating as well as development.
In conclusion, this investment will put us in position to shorten in-house development cycles, ensure high processing quality (semiconductor standard) and will allow for fast and flexible response to industry inquiries.

1 *The variable shaped electron beam lithography system SB254 from Vistec Electron Beam GmbH in the cleanroom.*
photo © Jens-Wolfram Erben





Material and reliability test equiment for MEMS and nanomembrane structures

A new set of test equipment has been installed with the Micro Materials Center at Fraunhofer ENAS. Using the support of the Fraunhofer 'Strategic Investment' funding scheme, the basis for analyzing micro and nano functional smart systems has been expanded. The new tool set allows material characterization of bulk and fracture mechanics properties as well as fatigue testing of MEMS, NEMS, thin films and other structures at micro and nano scale. One of the first research projects applying this new equipment has been conducted with Infineon Technologies, our long-term core industrial research partner. It has been dedicated to the mechanical strength of those nanomembranes made of polysilicon, which are part of various MEMS sensor and actuator components but also of most of the MEMS microphones we are all using with our smartphones. As these membranes need to be manufactured in highest volume at minimum cost, yield and reliability as well as fabrication efficiency are of utmost concern. The new set of test procedures developed in the joint PhD research effort applying the new indentation equipment has achieved the breakthrough in quality assurance that allows meeting all these constraints. It combines comprehensive characterization and metrology during development with highly efficient in-line assessments of the membrane systems during production.

2 *Reliability and strength testing of MEMS microphones applying the new nanoindentation tool.*
photo © John Brückner

MEMS Active Probe

Micro-electromechanical systems (MEMS) are typically batch-fabricated on wafers with diameters of 4'', 6'' or 8''. For the acceptance test of many micromechanical structures it is necessary to characterize essential parameters such as the modal frequencies and Q-factors. In order to characterize MEMS dynamically with an optimal signal to noise ratio the MEMS Active Probe has been developed and built. It covers the frequency range from 40 Hz up to 200 kHz (3 dB) with a sensitivity of up to 90 mV/nA. The output impedance is matched to 50 Ohm to be directly used with a spectrum analyzer. The polarization voltage for the generation of the currents to be measured is provided by the MEMS Active Probe itself. The bracket of the MEMS Active Probe can be used with common positioners and the probe tip is interchangeable. With the MEMS Active Probe it becomes possible to dynamically measure very low currents in the range of picoampere to nanoampere.

3 *The MEMS Active Probe is developed for dynamic measurement of very low currents on wafer and chip level.*
photo © Roman Forke

DISSERTATIONS

Dissertations in 2014

January 24, 2014
PhD: Jörg Bräuer
Topic: Erarbeitung eines Raumtemperatur-Waferbondverfahrens basierend auf integrierten und reaktiven nanoskaligen Multilagensystemen
Institution: Technische Universität Chemnitz

March 28, 2014
PhD: Sven Haase
Topic: The application of divergences in prototype based vector quantization
Institution: University of Groningen, The Netherlands

June 12, 2014
PhD: Holger Fiedler
Topic: Preparation and characterization of carbon nanotube based vertical inter connections of integrated circuits
Institution: Technische Universität Chemnitz

AWARDS

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2

3

The director of Fraunhofer ENAS Professor Gessner was awarded twice

On August 12th 2014, Dr. Hans-Otto Feldhütter, Head of Department Technology Marketing and Business Models of Fraunhofer-Gesellschaft, honored Professor Gessner with the Fraunhofer Medal on behalf of the Executive Board of Fraunhofer-Gesellschaft. He got this medal for his committed and successful work which is always focused on the strengthening and successful development of Fraunhofer ENAS.

In recognition of his significant achievements in microelectronics and microsystems technology at the TU Chemnitz as well as the development of a successful innovation network between Technische Universität Chemnitz, Fraunhofer Institute for Electronic Nano Systems ENAS and further scientific institutions and companies, Professor Thomas Gessner received the Medal of TU Chemnitz from the Rector Professor Arnold van Zyl.

Smart Systems Integration Award

Professor Bernd Michel has been awarded with the Smart Systems Integration Award at the Smart Systems Integration Conference & Exhibition in Vienna on March 26th 2014. He got this award for his excellent work in the field of reliability of micro and nano systems as well as integrated smart systems.

Professor Michel obtained Fraunhofer Medal

On April 30th 2014, Dr. Tomas Krämer, advisor of Fraunhofer ENAS within Fraunhofer-Gesellschaft, honored Professor Bernd Michel with the Fraunhofer Medal on behalf of the Executive Board of Fraunhofer-Gesellschaft. Professor Michel was honored for his active role in the development of two Fraunhofer institutes, Fraunhofer IZM and Fraunhofer ENAS. With the set-up of the Fraunhofer IZM a project group of his department was working in Chemnitz. This project group was the basis for the department Micro Materials Center of Fraunhofer ENAS.

Research Award 2014 of Fraunhofer ENAS

The researcher Dr. Sascha Hermann received the Research Award 2014 of Fraunhofer ENAS for his outstanding scientific work and research in the field of carbon nanotubes.

Commerzbank-Dissertationspreis (Commerzbank PhD Award)

On April 12, 2014, Dr. Ralf Zichner obtained the Commerzbank-Dissertationspreis 2013 for his excellent PhD in the field of RF communication of printed antennas in dielectric and metallic surroundings.

Best Poster Award on ALD2014

On the AVS Topical Conference on Atomic Layer Deposition 2014 ALD 2014 Mr. Xiao Hu (scientist within ITRG) received the best poster award for his poster "ALD of copper oxide from $(nBu_3P)_2Cu(acac)$ and wet O_2: a theoretical study". More than 200 posters have been presented at the conference.

Fellow of Fraunhofer ENAS

In 2014 three longtime department managers were honored as fellows of Fraunhofer ENAS for their scientific and application-oriented work of a lifetime. The first one is Prof. Bernd Michel, former head of department of the Micro Materials Center. Starting from crack and damage mechanics he developed together with his team methods for analyzing micro and nanosystems combining experimental methods and theoretical approaches.

The second one was Dr. Christian Kaufmann, the former head of department Layer Deposition of the Center for Microtechnologies of the Technische Universität Chemnitz. Starting in the early 90s Dr. Kaufmann was working on the development of actuators especially micro mirrors for different applications. His investigations were the basis for many industrial projects of Fraunhofer ENAS.

The third one was Dr. Andreas Bertz, the former head of department Lithography/Etch/Mask of the Center for Microtechnologies of the Technische Universität Chemnitz. He is one of the inventors of the so-called AIM (airgap insulating microstructure) technology. This technology is the basis of many high-precision MEMS and NEMS used for different applications starting from transport monitoring up to optimization of the capacity utilization of power lines.

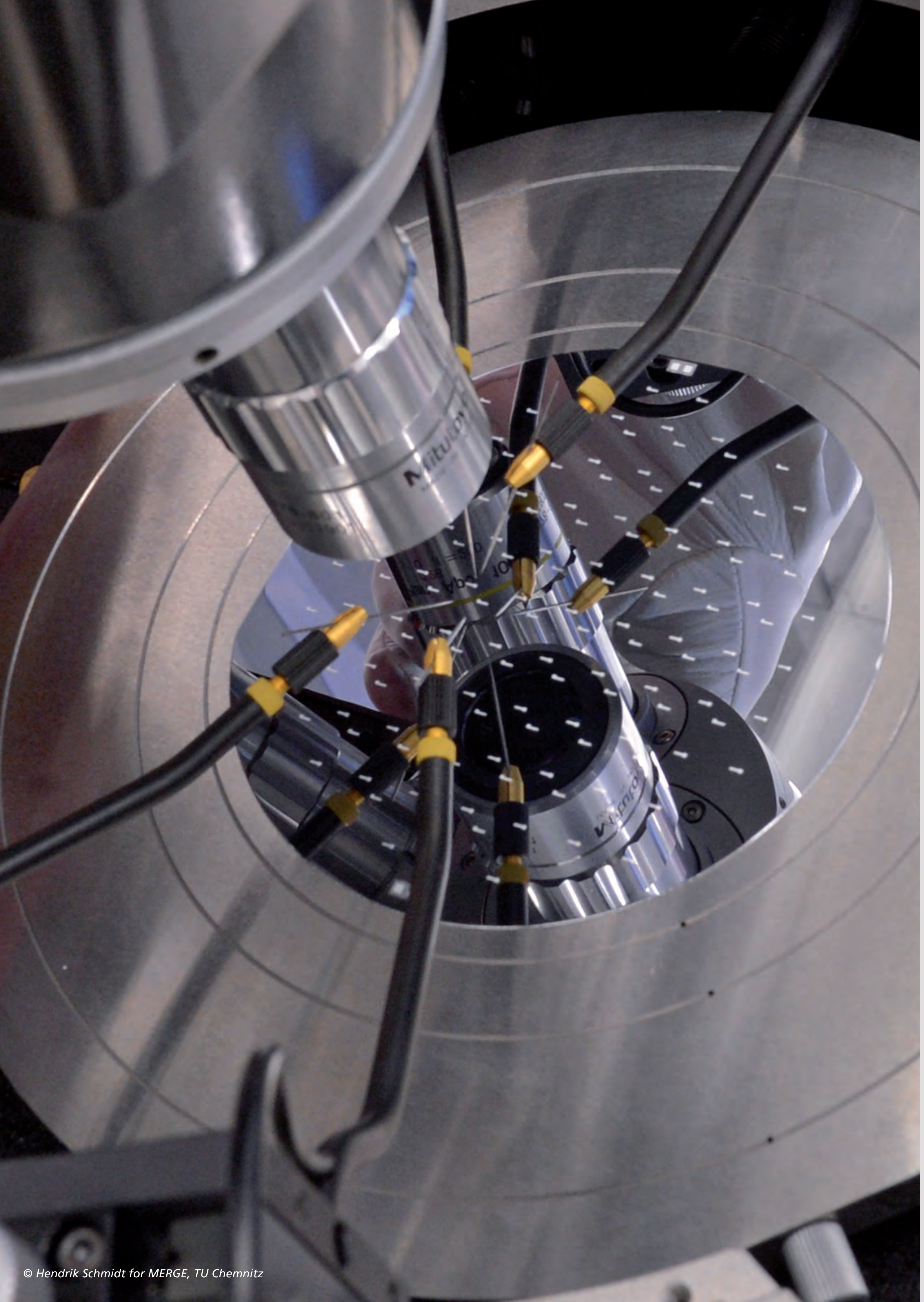
Retrospection to 2013

Within the annual report 2013 it was reported that Dr. Andreas Zienert won the Edgar Heinemann Prize of Technische Universität Chemnitz and Dr. Alexander Weiss the innovation award of the Schaeffler Stiftung in the field of product innovation. Both prizes were handed over in spring 2014.

1 *Dr. Hans-Otto Feldhütter, Fraunhofer-Gesellschaft, honored Prof. Thomas Gessner, Fraunhofer ENAS, with the Fraunhofer Medal.*
photo © Dirk Hanus

2 *The rector of the TU Chemnitz, Prof. Arnold van Zyl, honored Prof. Thomas Gessner with the Medal of TU Chemnitz.*
photo © Dirk Hanus

3 *On behalf of the Executive Board of Fraunhofer-Gesellschaft Dr. Tomas Krämer from the Fraunhofer-Gesellschaft handed to Prof. Bernd Michel the Fraunhofer Medal.*



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RESEARCH REPORTS

RESEARCH REPORTS

Smart systems are self-sufficient intelligent technical systems or subsystems with advanced functionality, which bring together sensing, actuation and data processing, informatics / communications. Therefore, these systems are not only able to sense but to diagnose, describe and manage any given situation. They are highly reliable and their operation is further enhanced by their ability to mutually address, identify and work in consort with each other. Depending on the complexity of their functionality they are divided into different generations.

The first and the second generation of smart systems entered into diverse applications starting from automotive and medical applications to standard consumer applications. The best-known example of a second-generation smart system is the ubiquitous smartphone, which has seen great commercial success. The third generation of smart systems will form the basis of the internet of things (IoT), the smart home, the smart city and smart production which are anticipated by the year 2025. Utilizing micro, nano and biotechnology, this third generation of smart systems integrates different functionalities such as signal processing, sensors, actuators and energy sources into one miniaturized package.

The particular strength of Fraunhofer ENAS lies in the development and prototyping of smart integrated systems. The single components are based on different technologies starting from silicon-based technologies, via polymer-based technologies up to printing technologies. System integration and interconnect technologies as well as test and reliability investigations and predictions are used to develop and prototype high-quality systems.

With the 2013 annual report, we started to combine our research reports according to different applications of smart systems. We showed that we are active in the field of smart electronics, smart medical systems, smart power, smart mobility and smart monitoring. With the last field, we address environmental monitoring as well as monitoring in the industrial sector.

We continue this philosophy with the 2014 annual report. It is a tradition to show only a selection of our work from the past year. We are thus refocusing on smart electronics, smart medical systems, smart power and smart monitoring. We also continue to work on topics of aerospace, automotive and logistics but without showing them in a separate chapter. You will find selected results in the chapter highlights.

In the 2014 report, for the first time, we included the Smart Sensing chapter which introduced newly developed sensors for a variety of applications.

FORSCHUNGSBERICHTE

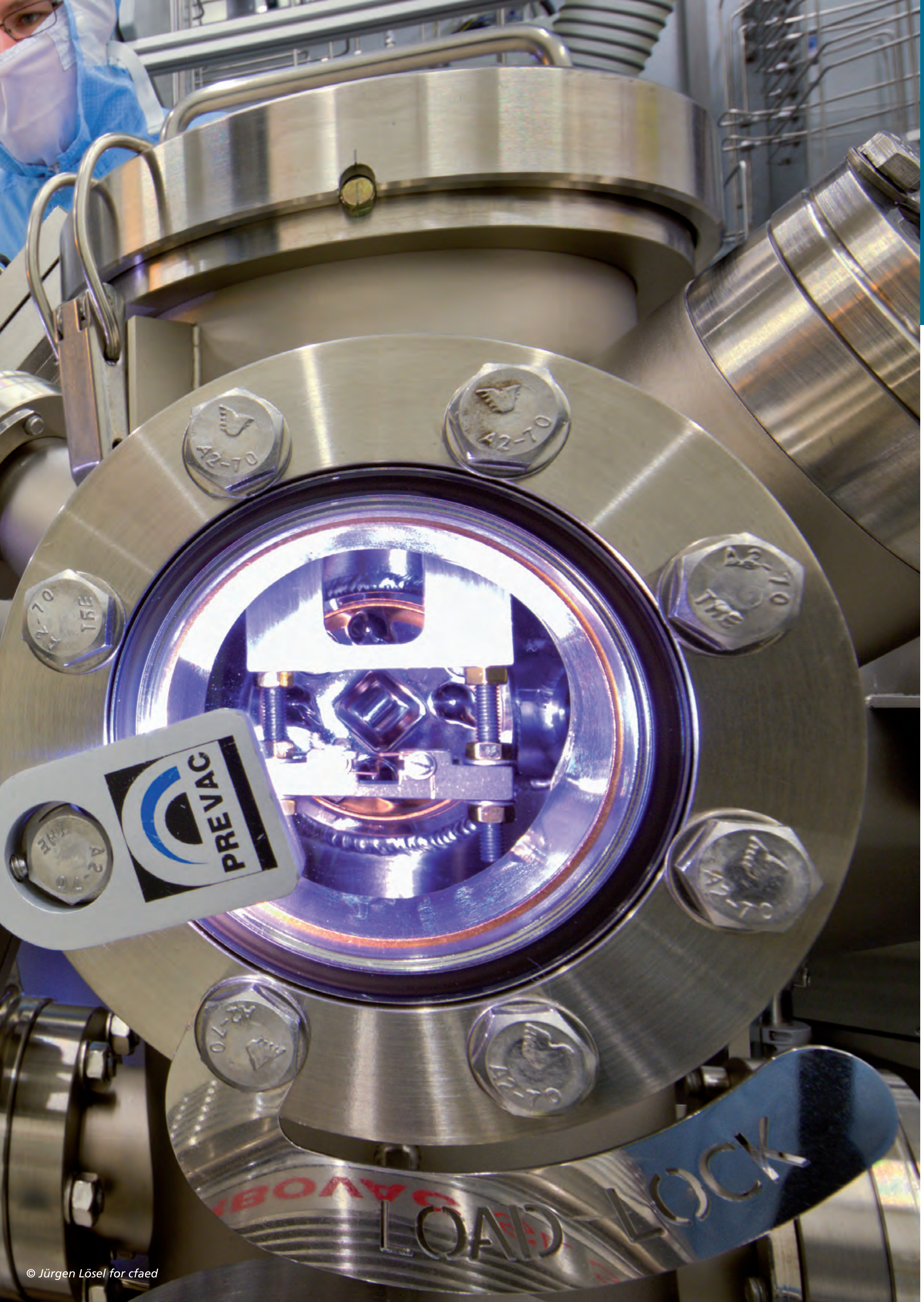
Smart Systems sind autarke intelligente technische Systeme oder Subsysteme erhöhter Funktionalität, die Sensorik, Aktorik und Datenaufbereitung und -auswertung sowie Informatik und Kommunikation kombinieren. Deshalb sind diese Systeme nicht nur in der Lage, verschiedene Daten zu messen, sondern sie können gegebene Situationen diagnostizieren, beschreiben und managen. Sie sind sehr zuverlässig und zunehmend mit der Fähigkeit ausgestattet, sich gegenseitig anzusprechen, zu identifizieren und in Konsortien zusammen zu arbeiten. Abhängig von der Komplexität ihrer Funktion werden sie verschiedenen Generationen zugeordnet.

Die erste und die zweite Generation dieser intelligenten Systeme ist bereits in diversen Anwendungen zu finden. Die Palette reicht vom Auto über die Medizintechnik bis hin zu Konsumgütern. Das be-kannteste Beispiel für ein intelligentes System der zweiten Generation mit einem großen wirtschaftlichen Erfolg ist das Smartphone. Die dritte Generation der Smart Systems wird die Basis bilden für das Internet der Dinge (IoT), das intelligente Haus, die intelligente Stadt (smart city) und Industrie 4.0. Diese Generation wird 2025 auf dem Markt sein. Unter Verwendung von Mikro-, Nano- und Biotechnologie wird die dritte Generation unterschiedliche Funktionalitäten, d.h. Sensoren und Aktoren mit der zugehörigen Elektronik und Energieversorgung, in einem miniaturisierten Gehäuse integrieren.

Die besondere Stärke des Fraunhofer ENAS liegt in der Entwicklung und der Erstellung von Prototypen intelligenter integrierter Systeme. Deren einzelne Komponenten basieren auf unterschiedlichen Technologien – Siliziumtechnologien, polymerbasierten Technologien bis hin zu Drucktechnologien. Systemintegrationstechnologien und Interconnecttechnologien sowie Test und Zuverlässigkeitsuntersuchungen und -vorhersagen werden zur Entwicklung und Prototypenherstellung hochqualitativer Systeme eingesetzt.

Mit dem Jahresbericht 2013 haben wir begonnen, unsere Forschungsberichte nach den verschiedenen Anwendungsgebieten intelligenter Systeme zu kombinieren. Wir haben gezeigt, dass wir auf den Gebieten Smart Electronics, Smart Medical Systems, Smart Power, Smart Mobility und Smart Monitoring arbeiten. Mit dem letztgenannten Bereich adressieren wir sowohl das Umweltmonitoring als auch das Monitoring im industriellen Sektor.

Wir setzen diese Philosophie mit dem Jahresbericht 2014 fort. Traditionell stellen wir nur eine Auswahl der im Jahr gelaufenen Themen vor. So fokussieren wir wieder auf Smart Electronics, Smart Medical Systems, Smart Power und Smart Monitoring. Wir haben ebenfalls an den Themen zur Luft- und Raumfahrt, der Automobilindustrie und der Logistik weitergearbeitet, stellen sie jedoch nicht in einem separaten Kapitel vor. Ausgewählte Ergebnisse dieser Thematiken sind im Kapitel Highlights zu finden. Erstmalig haben wir einen Abschnitt Smart Sensing eingefügt. Hier stellen wir neu entwickelte Sensorik für unterschiedliche Anwendungen vor.



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SMART ELECTRONICS

Smart Electronics addresses micro and nanoelectronics which is one of the key technologies of the 21st century. Not only the ongoing downscaling, known as More Moore, but also the integration of different functionalities, known as More than Moore, as well as the development of new nonsilicon-based materials, known as Beyond CMOS, are hot topics Fraunhofer ENAS is dealing with. Fraunhofer ENAS addresses:

- Materials, processes and technologies for advanced back-end of line schemes in micro and nanoelectronics
- Process technology for 3D integration, micro and nano systems
- Modeling and simulation of processes and equipments, of transistor devices as well as mixed-signal systems
- Characterization and reliability assessment, starting from BEOL components towards complete chip-package interactions including 3D integrated systems

Reliability of components and systems is always a main topic. The annual report 2014 includes results of long-term reliability testing performed under field conditions in a former mine as well as a novel strategy of virtual prototyping that allows the reliability of prospects of new designs and manufacturing processes to be assessed prior to initial fabrication. Moreover, fast and efficient modeling and simulation methods for mixed-signal systems are presented.

The 3D capable deposition of conductive nano-particle inks has been developed within the project CoolPod in the CoolSilicon cluster to form interconnects between the MEMS, electronics and board.

Moreover, special topics are addressed like plasma-assisted, in situ restoration processes for ultra low-k dielectrics and self-forming barriers at the interface between copper and dielectrics.

Results obtained within the cluster of excellence cfaed – Center for Advancing Electronics Dresden – have only been included in the chapter highlights. They are presented in more detail within the actual annual report from the Center for Microtechnologies at the Technische Universität Chemnitz.

Smart Electronics adressiert die Mikro- und Nanoelektronik, welche nach wie vor eine der Schlüsseltechnologien des 21. Jahrhunderts ist. Dabei spielen sowohl More Moore, More than Moore als auch Beyond CMOS eine wesentliche Rolle. Fraunhofer ENAS adressiert folgende Themen:

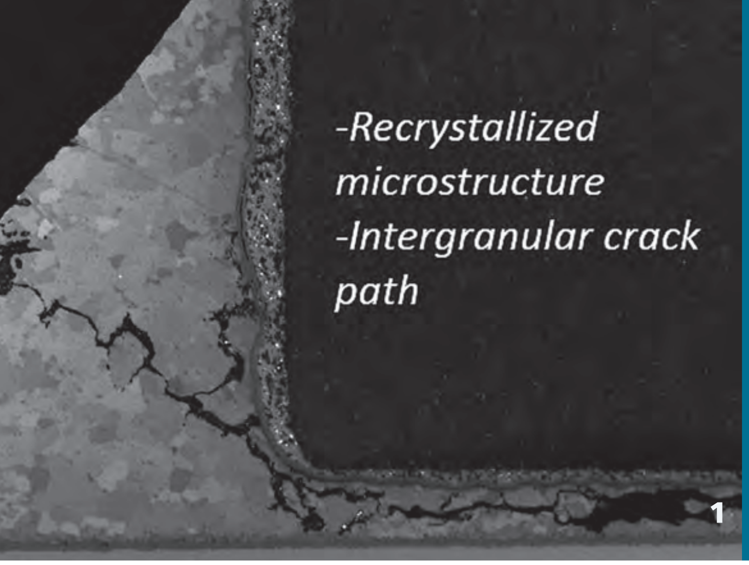
- Materialien, Prozesse und Technologien für die Mikro- und Nanoelektronik,
- 3D-Integration von Elektronik und Sensorik,
- Modellierung und Simulation technologischer Prozesse und Ausrüstungen (Equipments), Transistorbauelemente sowie Mixed-Signal Systeme
- Charakterisierung und Zuverlässigkeitsbewertung von BEOL-Komponenten bis hin zur Chip-Package-Wechselwirkung einschließlich 3D integrierter Systeme.

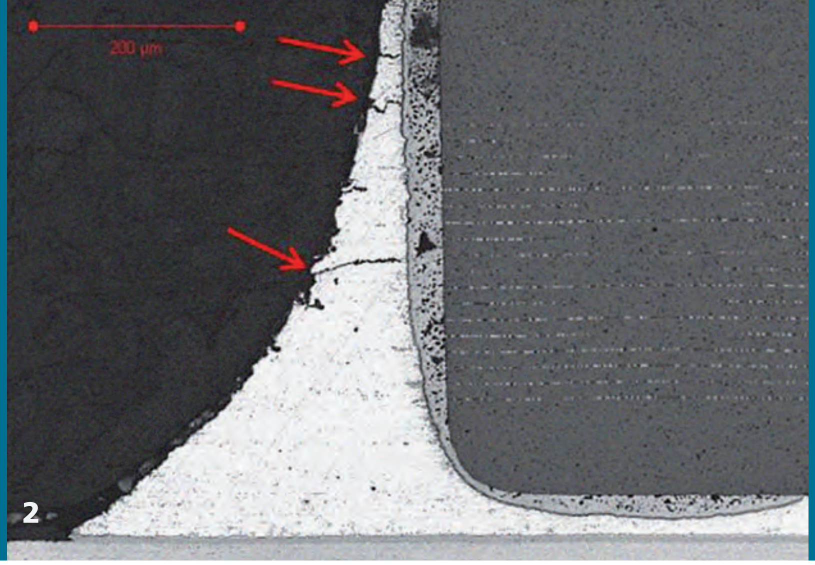
Zuverlässigkeit von Komponenten und Systemen ist immer ein Schwerpunkt. Im Jahresbericht 2014 werden Langzeitzuverlässigkeitstests unter Einsatzbedingungen sowie eine neue Strategie für das virtuelle Prototyping vorgestellt. Letztgenannte ermöglicht es, neue Designs und Herstellungsprozesse bereits vor der Produktion zu evaluieren. Darüber hinaus wird eine schnelle und effiziente Methode zur Modellierung Simulation von Mixed-Signal Systemen vorgestellt.

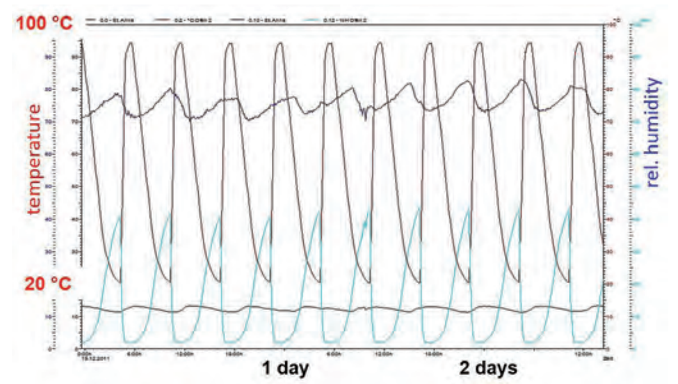
2014 wurde das 3D-Drucken von leitenden Nanopartikeltinten für die Verbindung von MEMS, Elektronik und Leiterplatte im Projekt CoolPod, einem Projekt des Spitzenclusters CoolSilicon, erfolgreich weiterentwickelt.

Darüber hinaus werden spezielle Fragestellungen adressiert, wie die plasmagestützte in situ Reparatur poröser Dielektrika und selbstformierende Barrieren aus Kupferlegierung.

Ergebnisse aus dem Exzellenzcluster cfaed – Center for Advancing Electronics Dresden – wurden bereits in den Highlights vorgestellt und sind ausführlich im aktuellen Jahresbericht des Zentrums für Mikrotechnologien der Technischen Universität Chemnitz enthalten.







LONG-TERM RELIABILITY TESTING UNDER FIELD CONDITIONS AND EVALUATION OF ACCELERATION FACTORS

Rainer Dudek, Marcus Hildebrandt, Kerstin Kreyßig

Cost-effective long-term fatigue testing in a former mine

Microsystems application in harsh environments, i.e. outdoor or offshore use of electronic or sensing devices, demand for long-term reliable and efficient functionality. However, there is a lack of testing data for long-term thermal cyclic under benign cyclic conditions as well as a on a reliable predictive model for the relation between accelerated tests failure and failure under use conditions, i.e. fatigue acceleration. This issue can be addressed by long-term testing. Relevant loadings are thermal cycling and moisture exposure. However, long-term testing requires expensive equipment and in case of thermal cycling a huge amount of electrical energy, which sums up to a big amount of running cost.

A unique solution was found to lower cost: why not using natural conditions as given in former mines and install a long-term reliability lab there? An almost constant environmental temperature of 8 – 12 °C, a humidity of 70 – 98 % and a high constant air flow, which allows for cooling without artificial freezing devices, is provided for free in that particular environment. Temperature chambers were installed in a former mine "Sankt Anna Fundgrube" dating back to the 18th century, which allow exposure of microelectronic systems to long-term thermal cycling environments at high relative humidity. Temperature cycling is computer-controlled and can be accessed via internet.

Testing of functional electronic assemblies subjected to automotive "under the hood" conditions

Long-term fatigue of lead-free solder joints was investigated at conditions of test coming close to automotive applications. Industrially produced electronic boards soldered with either tin-silver-copper alloy (SnAgCu 305) or Innolot were subjected to field cycles 23 °C / 93 °C, 6 hours cycle time. After 3 ½ and 4 ½ years or 4800 and 6500 cycles, respectively, the test boards were analyzed by electrical testing, shear testing and cross sectioning of selected samples. Although the new creep-resistant solder material Innolot was developed to enhance the limits of temperature, however, its performance at characteristic field temperatures is also of interest.

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After 6500 field cycles almost complete fatigue failure was observed from cross sectioning for large ceramic resistors (Fig. 1) and beginning fatigue failure for smaller resistors soldered with SnAgCu. The field cycling induced damage patterns were compared to those from test cycling –40 / 150 °C. The microstructural degradation observed for the field reliability tests suggested that the failure mechanism of SnAgCu is similar to that seen with test cycles. Recrystallization causes a fine grain structure and intergranular fracture occurs, sometimes with crack branching. Comparably little fatigue effects were seen with Innolot for the same components, however, different and new types of brittle cracking have been identified for test- und field cycling. For field cycling cracks occurred at the solder meniscus (Fig. 2), which are a new type of failure. In the case shown, they do not affect the electrical functionality, but similar cracks can result in a failure risk for other solder joint geometries.

Comparison of theoretical predictions for fatigue life to testing results

For SnAgCu acceleration of thermal shock cycling with respect to field cycling was seen to be approximately AF=11. This acceleration factor was compared with calculations based on different published acceleration laws (Norris/Landzberg equations) and on numerical simulations. Evaluation by acceleration laws resulted in a broad range of acceleration factors which differed by several hundred percent, what can lead to a significant overestimate of field fatigue life. Numerical simulations combined with Coffin/Manson or Morrow type criteria underestimated acceleration by up to two hundred percent, i.e. these predictions are on the safe side.

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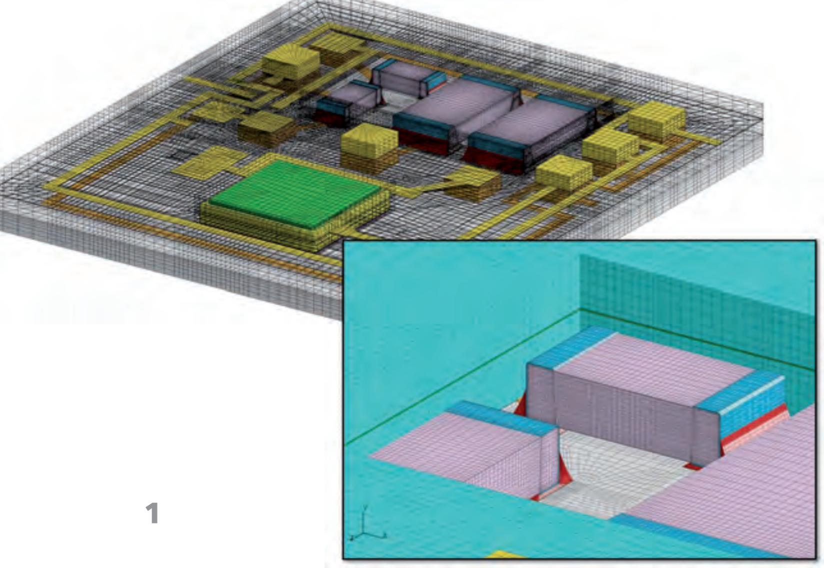
Die Nutzung von mikrotechnischen Aufbauten unter harschen Einsatzbedingungen erfordert eine hohe Langzeit- Zuverlässigkeit für den Betriebsfall. Durch den Einsatz neuer komplexerer Baugruppen aber auch neuer Verbindungswerkstoffe besteht ein Mangel an Aussagen zum Zuverlässigkeitsverhalten unter solchen feldnahen Beanspruchungsbedingungen. Diese Bedingungen bestehen häufig vornehmlich in langsamen Temperaturwechselbeanspruchungen mit relativ geringem Hub und hohem Feuchteeinfluss. Die Tests sind nicht nur sehr zeitaufwendig sondern erfordern unter Laborbedingungen auch einen extrem hohen Energieaufwand. Es wurde daher nach einer energiesparenden Variante für die Tests gesucht und in einer ungewöhnlichen Lösung realisiert: Durch Platzierung von Temperaturkammern in einem früheren Bergwerk können feldnahe Bedingungen ohne künstliche Kühlung und Befeuchtung realisiert werden, da ganzjährig ein großes Luftvolumen mit einer Temperatur von ca. 8 – 12 °C, einer relativen Feuchte von 70 – 98 % und einer hohen Luftströmung verfügbar ist. Es wurden aus laufenden Feldtests an industriell gefertigten elektronischen Baugruppen mit einer Thermozyklusbeaufschlagung 21/93 °C, 6 Stunden Zyklusdauer, nach. 3 ½ Jahren und 4 ½ Jahren (entsprechend 4800 und 6500 Feldzyklen) Proben entnommen und analysiert. Dabei konnten materialabhängige Schädigungsprozesse durch Rissbildungen in den Lötverbindungen von keramischen Bauelementen festgestellt und mit theoretischen Prognosen verglichen werden, wobei verschiedene Prognostikmodelle starke Abweichungen von der Realität gezeigt haben. Darüber hinaus wurden für Innolot-Verbindungen ein neuer Schädigungsmode gefunden.

1 *Characteristic damaged SnAgCu solder joints after 4 ½ years of thermal cycling (6500 field cycles).*

2 *Characteristic initial damage at Innolot solder joint after 3 ½ years of thermal cycling (4800 field cycles).*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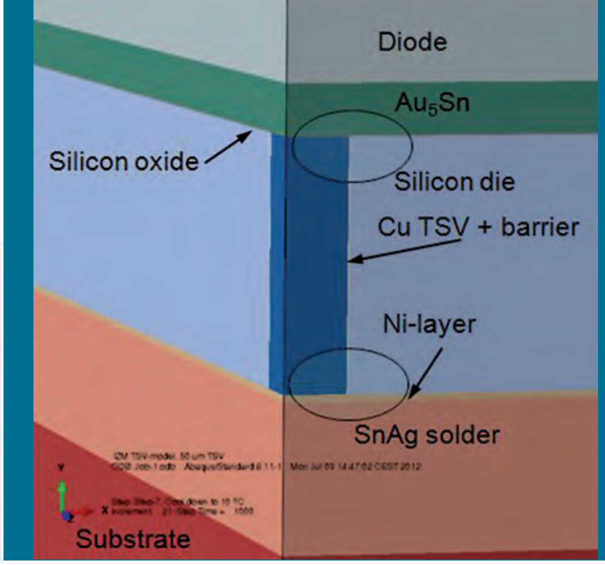

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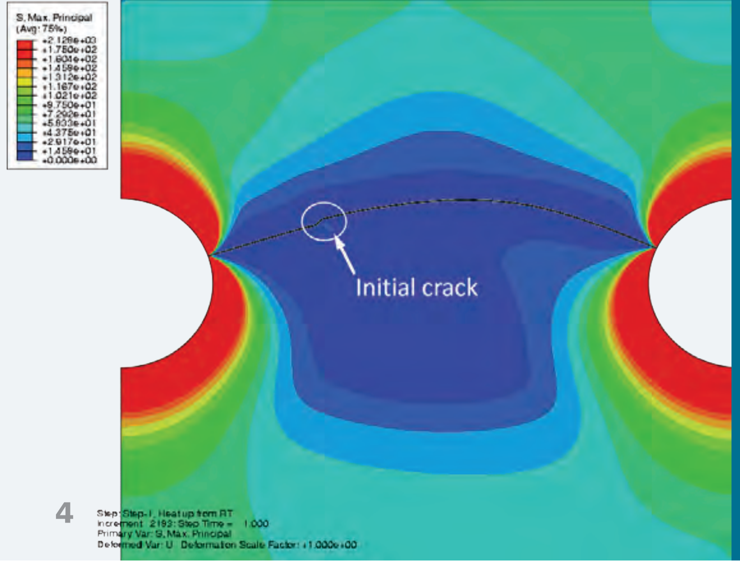
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5

RELIABILITY OPTIMIZATION FOR THE NEXT GENERATION OF LED-BASED SMART AND COMFORTABLE LIGHTING SOLUTIONS

Jürgen Auersperg, Sven Rzepka

The incandescent light bulb, patented by Thomas Edison in 1880, is now an endangered species. It is condemned to extinction because it no longer meets the technical requirements of the 21st century. A conventional light bulb converts just 5 % of the energy it consumes into light, while the remaining 95 % is emitted as heat. That is why Europe has banned all frosted and high-energy incandescent light bulbs from manufacturing and selling in the EU member states in 2008.

Today, light-emitting diodes, or LEDs for short, have an efficiency of up to 90 %. They are smaller, more flexible and offer far more scope for innovative lighting design solutions. On the other hand, the manufacturing costs of LED-based lighting systems have still been relatively high and the light produced often failed to meet customer requirements. An interdisciplinary team of experts drawn from 30 European companies and research institutes has therefore participated in the EU's EnLight project, which aimed for creating sustainable and energy-efficient lighting systems based on LEDs that emit light compatible with all the situation-specific requirements for human comfort.

Within this project, members of the Micro Materials Center at Fraunhofer ENAS have developed and implemented a novel strategy of virtual prototyping that allows assessing the reliability prospects of new designs and manufacturing processes already prior to any first fabrication of the systems. This way, the physical development can directly start with the most promising option – avoiding time consuming learning cycles. Particular attention has been paid to 3D integration as important key technology for advanced LED lighting solutions. Within this scope, thermal through silicon vias (TSV) are seen as elegant way to efficiently transfer the heat from the power LED component to the heat spreading structures on the backside of a substrate. However, the thermal mismatch between the copper of the TSV and silicon of the dies also generates novel challenges for the system reliability as well as for the reliability analysis and prediction. Multiple failure modes occur simultaneously: interface delamination, bulk cracking and material fatigue. Therefore, the new simulation strategy has been developed for the complex virtual assessment. The strategy utilizes an interaction integral approach within the simulative DoE studies based on X-FEM fracture mechanics analysis in order to anticipate the crack propagation paths and speeds in silicon realistically for each design and process option. The DoE-based response surface methodology provided all means for a very efficient assessment and pre-optimization of the intended thermal TSV-approach for all the various LED packaging applications. The new assessment method of virtual prototyping delivers 'first time right' design solutions in minimum time. It speeds up the development cycle for new LED-based lighting solutions substantially.

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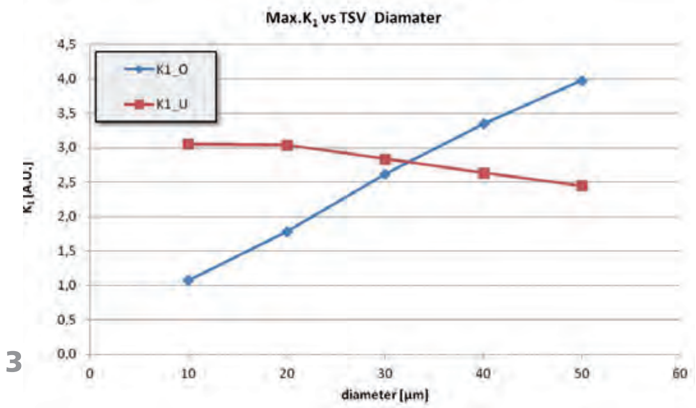

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Even with its modest contribution to the over-all project results, the team involved at Fraunhofer ENAS is very proud to announce that EnLight has received the 2014 ENIAC Innovation Award at the European Nanoelectronics forum in Cannes on November 26th-27th.

The award was presented by Dr. Andreas Wild and Dr. Yves Gigase, respectively Executive Director and Head of Operations, formerly of the ENIAC JU and now of the ECSEL Joint Undertaking that has now taken up the support of the ENIAC projects.

In his speech, Dr. Wild highlighted once more the importance of semiconductor technology as a core European competence, which fully delivers on its promise of innovation when taken up by leading actors along the full value chain; from device suppliers, software and integration specialists to system developers. In this way, the EnLight project has been exemplary in bringing together such key actors in a project of significant size (more than 41 million euros R&D investment) to achieve results of genuinely high value to the partners.

Heutige Leuchtdioden sind mit ihrem Wirkungsgrad von bis zu 90 % nicht nur kleiner als die von Thomas Edison 1880 patentierte Glühbirne, sie bieten auch mehr Raum für innovative Lichtdesign-Lösungen. Ein interdisziplinäres Team von Experten aus 30 europäischen Unternehmen und Forschungsinstituten fand sich daher im EnLight-Projekt der EU zusammen, um nachhaltige und energieeffiziente Beleuchtungssysteme auf Basis von LEDs zu entwickeln, die Licht entsprechend den menschlichen Komfortanforderungen erzeugen sollen. Mitarbeiter des Micro Materials Center am Fraunhofer ENAS haben darin wertvolle Zuarbeiten zur Sicherung der Zuverlässigkeit neuer Designs und Fertigungsprozesse beigesteuert. Besonderes Augenmerk wurde auf 3D-Integration und thermische TSVs für moderne LED-Packaging-Lösungen gelegt. Multiple Versagensmodi wie Bruch, Delamination und Materialermüdung wurden mittels bruchmechanischer Ansätze, simulativem DoE und dem Einsatz von X-FEM analysiert. Lebensdauermodelle und Gestaltungshinweise wurden abgeleitet. Das Projekt EnLight wurde auf dem europäischen Nanoelektronik-Forum in Cannes mit dem ENIAC 2014 Innovation Award ausgezeichnet – als Beispiel für ein erfolgreiches europäisches Großprojekt, das jedem Partner entlang der gesamten Wertschöpfungskette jeweils spezifische Ergebnisse von hohem Nutzwert brachte, die anders nicht erreichbar gewesen wären.

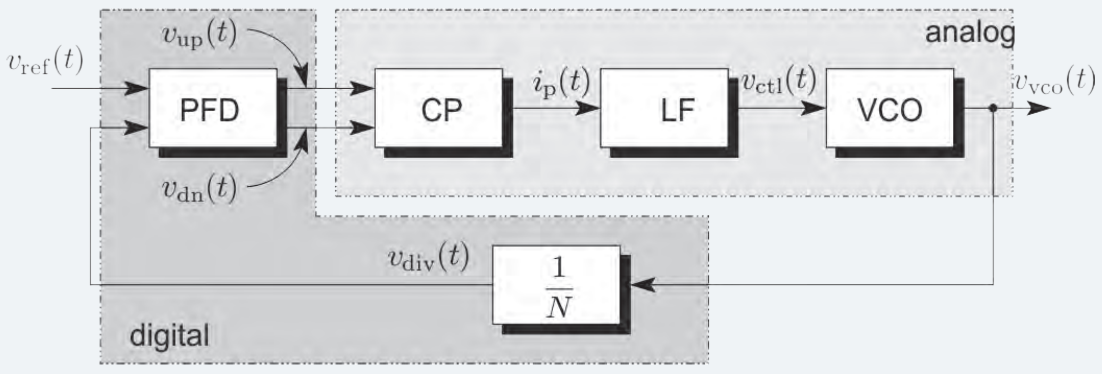
1 *2D/3D wafer-level integration of a power module.*

2 *Detail of the design of the LED-package in the surrounding of a copper-TSV.*

3 *K_I-progress of both initial material interface crack vs. TSV diameter.*

4 *Crack propagation path of a crack initially located between the 2 TSVs during heat up from stress free temperature 60 °C to 430 °C.*

5 *Award presentation at the European Nanoelectronics Forum in Cannes on November 26th-27th.*



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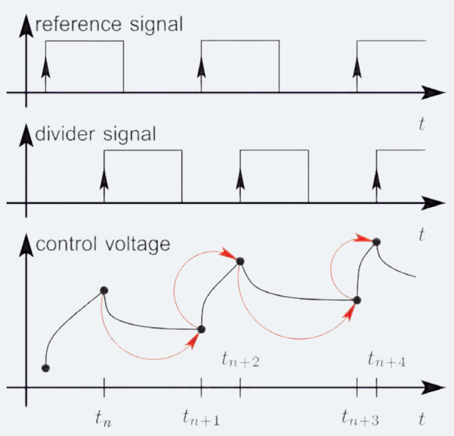

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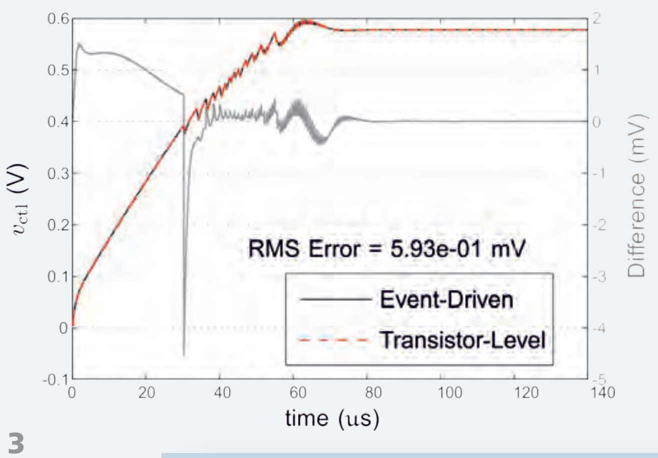

3

VERY FAST AND EFFICIENT MODELING AND SIMULATION METHODS FOR MIXED-SIGNAL SYSTEMS LIKE THE CP-PLL

Christian Hangmann, Ulrich Hilleringmann, Christian Hedayat

Introduction

The CP-PLL is an integrated mixed-signal circuit and is used in modern systems like mobile phone and wireless internet access [1,2]. Since a CP-PLL used for frequency synthesis has a mixed-signal architecture (Fig. 1), it is difficult to use general theory to characterize its nonlinear behavior and challenging to achieve a robust system design [3]. Therefore, linear models and simulations are used. The disadvantages are the limited validity, the a priori approximation and the long simulation time. Thus, it is necessary to use a more time-efficient modeling approach to consider nonideal and nonlinear effects.

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Event-driven modeling

The Event-Driven (ED) model is based on the phase information of the reference and feedback signal of the PLL [4]. Only when a rising edge triggers the PFD, the loop responds to the phase error (Fig. 2). Thus, it is sufficient to calculate all PLL-states at the triggering events only. These calculation steps correspond to an iterative algorithm allowing to model an arbitrary ordered Fractional-N and Integer-N PLL including nonlinear and nonideal effects [5].

Event-driven vs. transistor level

To validate the enhanced ED model, first the PLL components are characterized separately based on Transistor Level (TL) simulations. The resulting nonlinear and nonideal characteristics are then included in the ED model. Afterwards the PLL behavior is simulated using both the ED model and the TL platform and results are shown in figure 3. Both simulations are very similar. The difference between both has its maximum within the locking process where the CP-PLL exhibit a chaotic behavior [4]. After locking the difference converges to zero. Although the ED model is nearly as accurate as the TL platform, the simulation time is highly decreased (see table).
By using this model the characterization and design considering nonlinear and nonideal effects can be done very efficiently [6]. Additionally, Monte-Carlo-Simulations become very time-efficient.

	Sim.-Time	Rel. RMS Error	Speed-Up
Transistor Level	4919.13 s	–	–
Event-Driven	0.67 s	0.1 %	≈7342

Moderne Systeme bestehen aus mehreren Komponenten, die klein und hoch integriert realisiert werden müssen. Des Weiteren beinhalten diese Systeme oft eine drahtlose Kommunikation, wobei die Frequenzsynthese ein wichtiger Bestandteil ist. Die CP-PLL ist ein hochintegrierter Baustein zur Realisierung der Frequenzsynthese. Da sie gemischt digital-analog aufgebaut ist, stellt der robuste Systementwurf eine Herausforderung dar. Speziell bei Berücksichtigung von nichtlinearen und nichtidealen Effekten ist die allgemeine Theorie nicht anwendbar. Daher werden lineare Modelle und Simulationen verwendet. Auf Grund des Kompromisses zwischen Genauigkeit und Simulationszeit wird in diesem Artikel eine hoch effiziente und akkurate Simulationsmethode vorgestellt. Hierzu werden die Komponenten separat auf Transistor-Level charakterisiert und entsprechende makroskopische Parameter im ereignisgesteuerten Modell eingebunden. Die Ergebnisse zeigen die Genauigkeit (0,1% rel. RMS) und die Effizienz (Speed-Up > 7000) des gezeigten Modells gegenüber der Transistor-Level-Plattform.

Conclusion

To obtain a very time-efficient simulation methodology for mixed-signal systems, the PLL components are characterized separately based on TL simulations and macroscopically included into the ED model. The comparison of the TL model and the ED approach shows that both simulation results are very similar. Thereby the ED model is applicable to consider nonlinear and nonideal effects. Additionally, it is shown that the ED technique is a very time and computer resource-efficient approach due to speed-up factors up to 10000 compared to TL simulations. Thus, this ED model can be used to efficiently characterize and design mixed-signal systems considering nonlinear and nonideal effects.

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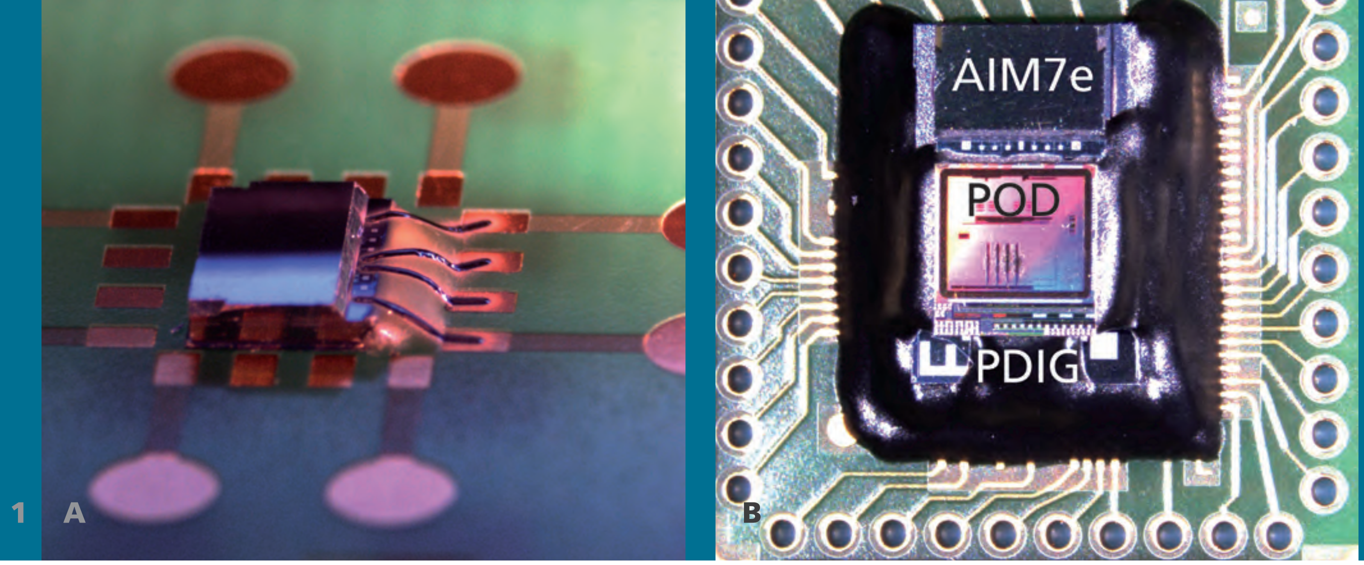
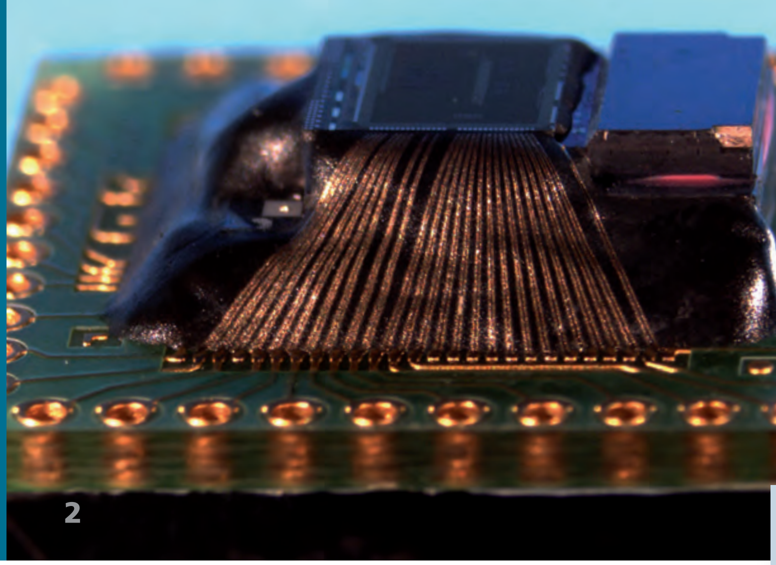
[6] Hangmann; Hedayat; Hilleringmann: Stability analysis of a charge pump phase-locked loop using autonomous difference equations. IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 61, no. 9, 2014, pp. 2569–2577.

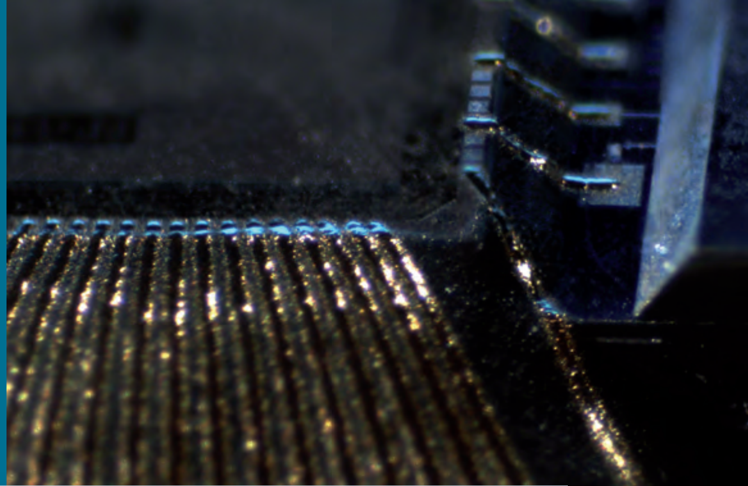
1 *General diagram block of a charge-pump PLL system.*

2 *Concept of the event-driven modeling and simulation.*

3 *Excellent matching between the event-driven and the transistor level simulations.*







COOL POD: PRINTED 3D CHIP-2-BOARD INTERCONNECTS

Tobias Seifert, Mario Baum, Frank Roscher, Maik Wiemer, Thomas Gessner

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The possibilities of the Aerosol Jet® deposition are promising regarding packaging issues for electronic products and micro-electromechanical systems. The direct and maskless deposition of metal-based nanoparticle inks for chip interconnects as well as the different material compatibilities within usual assembly processes could be developed within the R&D project CoolPod, a CoolSilicon project funded by SAB-Foerderbank.

Goal of the CoolPod project was the development of a sensor system including an inertial sensor, an ASIC and a special wake-up generator device for low power consumption while sleeping. Each chip had a different thickness which makes it difficult to connect the components to the board by printing. Here, printing of interconnects could be used as an alternative to conventional wire bonding in terms of enhancing the degree of 3D system integration with synergies in reduction of size and of material consumption.

The stacked assembly “CoolPod” consisting of power down interrupt generator (PDIG), AIM-7e acceleration sensor (AIM7e) and ASIC was accomplished on top of a customized PCB by Microelectronic Packaging Dresden GmbH (MPD), Germany. The all over height of fabricated stack was measured with 3.8 mm whereas the footprint was identified with an area of 90 mm x 100 mm. The device itself is capable to wake up electronic microsystems from so-called power down mode due to mechanical impacts from environment using a self-generated energy impulse [see “Piezoelectric low-power MEMS with aluminum nitride” on page 87]. Thereby energy could be saved significantly in comparison to existing solutions. The involved single chips are assembled manually and group-wise whereby stacking was established by depositing underfiller material between devices and PCB manually. Dam material was supposed to generate smooth topographic transitions between contact coordinates of each single device for better printing results between contact coordinates of each single device. Stacked assemblies were separated using dicing technology after fabrication due to handling reasons during printing. The center to center distance between two neighboured contacts of the ASIC were designed with a width of approximately 75 µm whereby one single contact pad is designed with a width of 50 µm what requires printed line widths for interconnects of 25 µm. A detailed view of a single stacked device is shown in figure 1.

To reduce the problems of insufficient aerodynamic focussing due to high standoff distances the stacked device was inclined by 17.5° in reference to platen holder. This inclined position effectively decreases the overall distance standoff height between printhead and topography that has to be printed. Additionally the inhomogeneous topography of dam material leads to another inconsistency in terms of constant standoff height. Here in between neighboured printed interconnects at comparable level of height clearly strong differences in aerodynamic focussing are visible. The effort of performing such a kind of printing process however is time consuming, as the PCB has to be rotated according to the considered contacts that have to be printed sidewise. Also connecting of multiple stacked devices onto one extensive and inclined substrate is only possible in a limited manner at the given process setup because of possible collisions between printhead and substrate. In figure 2 exemplary one completely contacted sample of CoolPod is shown.

Aerosol Jet printing was successfully evaluated as key enabling material transfer technology in the field of alternative approaches for 3D integration with systems from the field MEMS/NEMS packaging. With stacking of single devices, savings in footprint and volume could be achieved.

In parallel this developed packaging technology could be used for several other applications which would lead to additional innovations in the field of micro technology and electrical interconnects over 3D topographies.

Acknowledgment

Partners of the project were: Electronic Design Chemnitz GmbH, Microelectronic Packaging Dresden GmbH and TU Chemnitz. The work related to integration technologies of single and stacked components on PCB was partly supported by the European Union (EFRE) and by the Free State of Saxony, Germany, within the research project CoolPod funded by SAB-Foerderbank (100107775).

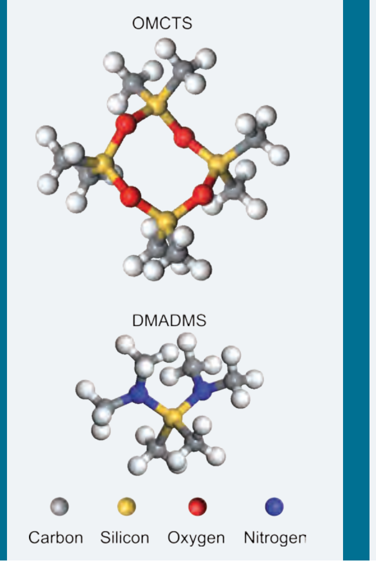
Europäische Union
Europa fördert Sachsen.
EFRE
Europäischer Fonds für regionale Entwicklung

Das Projekt CoolPod hatte zum Ziel, den technischen Nachweis der Machbarkeit eines mikromechanischen Power-Down-Interrupt-Generators (PDIG) zu erbringen. Der Wandler kann aufgrund mechanischer Bewegungen elektronische Mikrosysteme aus dem sogenannten Power-Down-Mode wecken, um dadurch im Vergleich zu bestehenden Lösungen Energie in signifikantem Umfang einzusparen. Einen weiteren Schwerpunkt bildeten Untersuchungen zu einer dreidimensionalen Packagingtechnologie für Sensorik und Application-Specific-Integrated-Circuit (ASIC). PDIG, ASIC und Sensor müssen in geeigneter Weise in einem Gehäuse kombiniert und sowohl mechanisch als auch elektrisch verbunden werden. Ein weiteres wissenschaftlich-technisches Arbeitsziel war die Entwicklung neuer Packaging-Ansätze. Hierzu sollten neue Kontaktierungsmethoden beitragen, die durch Drucken von Leitbahnen über dreidimensionale Oberflächenstrukturen erfolgten. Die Substitution von Drahtbondkontakten durch gedruckte Leitbahnen unter Nutzung des Aerosol-Jet-Verfahrens war das zentrale Forschungsthema des Fraunhofer ENAS im Projekt. Durch Stapeln der Einzelchips und das Drucken wurde eine kleinstmögliche Bauform erreicht.

1 *Single Chip printed interconnects onto prepared sample AIM7e (A) and top view (B) of stacked assembly “CoolPod” with AIM7e acceleration sensor, ASIC and PDIG.*

2 *Overview of printed interconnects of stacked assembly “CoolPod” between ASIC (top level) and PCB.*

3 *Detailed view of printed interconnects between ASIC, AIM7e and PCB at ASIC (top level).*



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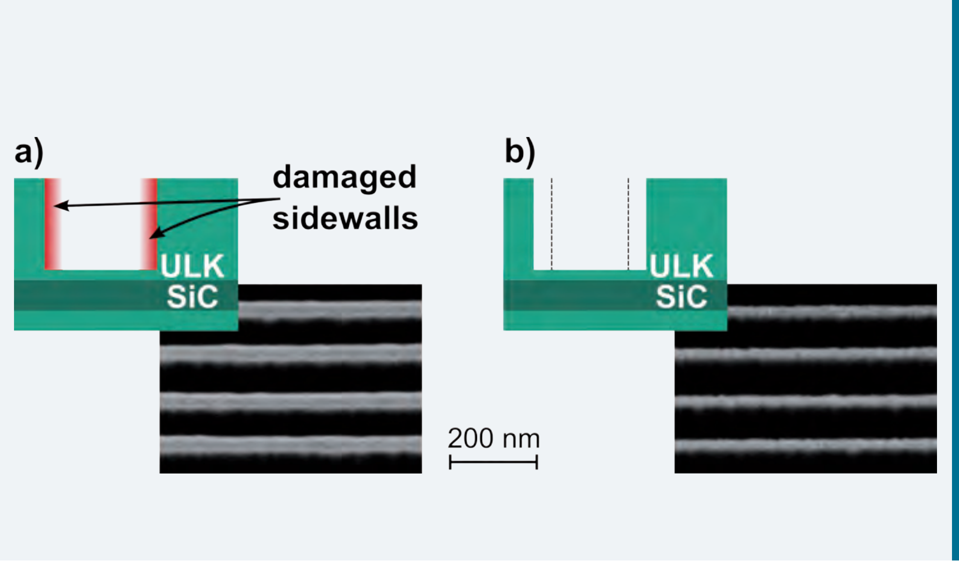

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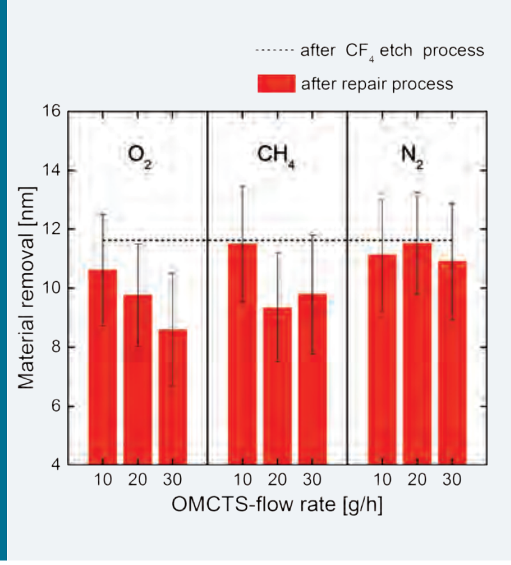

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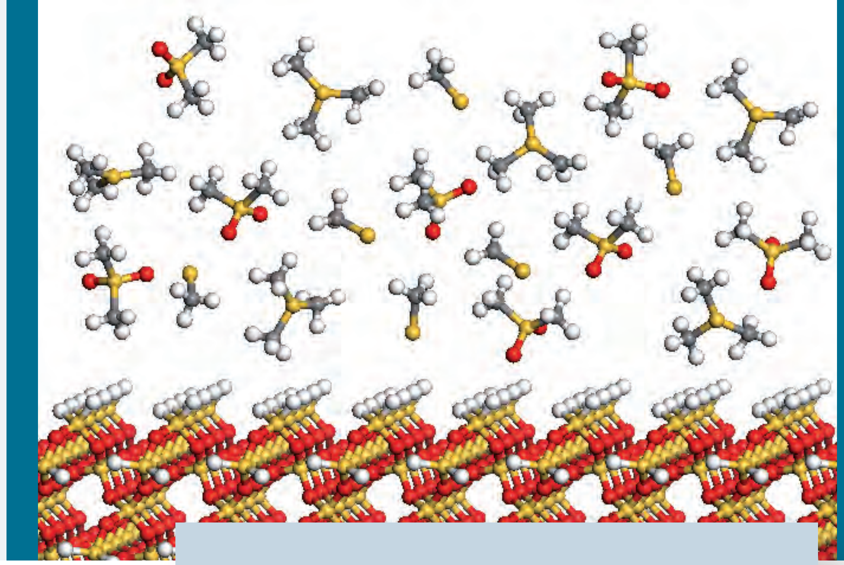

4

EXPERIMENTAL AND THEORETICAL INVESTIGATIONS ON A PLASMA ASSISTED IN SITU RESTORATION PROCESS FOR ULK DIELECTRICS

Nicole Köhler, Tobias Fischer, Anja Förster, Christian Wagner, Jörg Schuster, Sven Zimmermann, Sibylle Gemming, Stefan E. Schulz and Thomas Gessner*

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Plasma damage to ultra low-k (ULK) materials by pattering processes cannot be completely avoided [1]. Therefore, restoration processes are still of high interest for further k-value improvement. There exists a large number of different silylation processes that repair polar Si-OH bonds to nonpolar Si-O-Si-CH_3. Besides a poor integration in current technologies the repair effect is often limited to the surface due to the size of silylation molecules compared to the pore size [2]. The plasma assisted in situ restoration process, developed at Fraunhofer ENAS, overcomes these problems by easy integration in existing process tools and process flows as well as a reduced size of repair species due to plasma fragmentation to enhance the diffusion behavior.

The experimental setup is based on an Applied Materials ASP chamber, which is embedded in a Centura Etch Cluster Tool. This enables a transfer of wafers between etch and repair chamber without vacuum break and prevents the damaged material from moisture uptake. The remote plasma produces radicals without exposing the samples to plasma to avoid UV radiation and ion bombardment. The repair liquids are evaporated by a direct liquid injection evaporation system.

For preliminary investigations OMCTS, as oxygen containing precursor and DMADMS as non-oxygen containing precursor (Fig. 1) were studied on blanket wafers. Patterned samples were analyzed regarding the depth of damaged material on the sidewalls. Since damaged ULK material can be wet etched by HF [3], the trench width of SEM topview images was measured by gray scale analysis before and after the wet etch to calculate sidewall damage, like it is shown in figure 2.

Theoretical investigations

The simulation of fragmentation and repair reactions supports the experimental results and can help to obtain new insights into the plasma repair mechanism. Two different methods, density functional theory (DFT) and molecular dynamic (MD), were chosen to solidify the results. The fragmentation of the repair precursors OMCTS and DMADMS were investigated first. The most favorable fragmentation reaction for OMCTS is into four $OSi(CH_3)_2$ groups, whereas five oxygen containing repair fragments are possible in general. The advantage of these groups is the ability to occupy damage induced Si-H bonds without the necessity of silanol formation. The fragmentation of DMADMS results primarily in $Si(CH_3)_3$, especially in a methyl rich environment. The calculations have shown that the most effective repair fragments to occupy OH-groups and dangling bonds contain three methyl groups or two oxygen atoms. It could be seen that the repair fragments must contain at least one oxygen atom to be able to repair a Si-H group.

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Experimental results

The experimental results clearly demonstrated that OMCTS is more effective for a plasma restoration process. This is consistent with the theoretical investigations, where only oxygen containing repair fragments can occupy a Si-H group. These dangling bonds are more expected than silanol groups due to the in situ handling. The process parameters temperature, precursor flow rate and the admixing of additional gases were investigated. The results have shown that the combination of these process parameters have to be chosen carefully to improve a repair reaction. Notably, the admixing of oxygen to the repair plasma influences the restoration process significantly. With too low OMCTS flow rates (< 5 g/h) a damaging behavior could be observed, which can be turned into a repairing effect after increasing OMCTS flow rate. The in situ plasma repair shows a sidewall restoration efficiency of more the 25 % (Fig. 3).

Outlook

Ongoing investigations will include the impact of post-treatments as well as the mechanical characterization of the plasma restored material. Moreover, simulations of repair reactions in bigger silicon oxide clusters will be investigated (Fig. 4) to take the steric hindrance into account. An optimized plasma assisted in situ restoration process in combination with a well-adjusted etch process can reduce the sidewall damage problem significantly.

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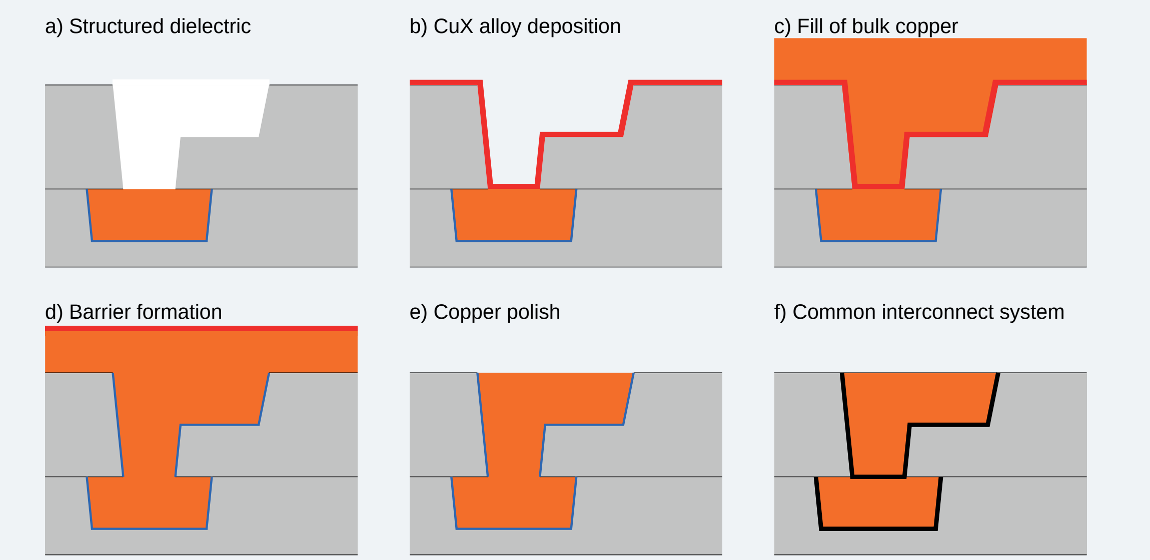
Plasmaschädigungen beim Ätzen von Ultra-low-k Materialien (ULK) können nicht vollständig verhindert werden. Die Schädigungen führen zu erhöhten Dielektrizitätswerten und somit zu höheren RC-Produkten im Leitbahnsystem. Deshalb wurde am Fraunhofer ENAS ein in situ Plasma-Reparatur-Prozess entwickelt, welcher eine bessere Reparatureffizienz aufweist als entsprechende Silylierungsprozesse. Zudem erfolgt der Reparaturprozess ohne Vakuumunterbrechung, so dass durch die Plasmaeinwirkung aufgebrochene Bindungen nicht erst durch Wassermoleküle abgesättigt werden können.
Es wurden zwei Reparaturchemien untersucht, OMCTS als sauerstoffhaltiger Präkursor und DMADMS ohne Sauerstoffbestandteile. Die Ergebnisse der theoretischen Untersuchungen, die Simulation der Fragmentierung der Präkursoren und des Reparaturprozesses an den geschädigten Bindungen stimmen mit den experimentellen Ergebnissen sehr gut überein. Der sauerstoffhaltige OMCTS-Präkursor ist besser für die Reparatur der geschädigten Bindungen geeignet und dessen Wirkung wird nochmals begünstigt durch Zumischung von O_2 zum Prozessgas. Es konnte eine Reparaturwirkung von mehr als 25% erreicht werden.

1 *Molecular structure of the used repair precursors octamethylcyclotetrasiloxane (OMCTS) and bis(dimethylamino)dimethylsilane (DMADMS).*

2 *a) schematic cross section and SEM top view of an etched trench and b) after the removal of sidewall damaged material.*

3 *Material removal of sidewall-damaged and -repaired 62 nm trenches at different OMCTS-flows and gas additives.*

4 *Silicon oxide cluster with –OH and –H groups with its appropriate repair fragments.*



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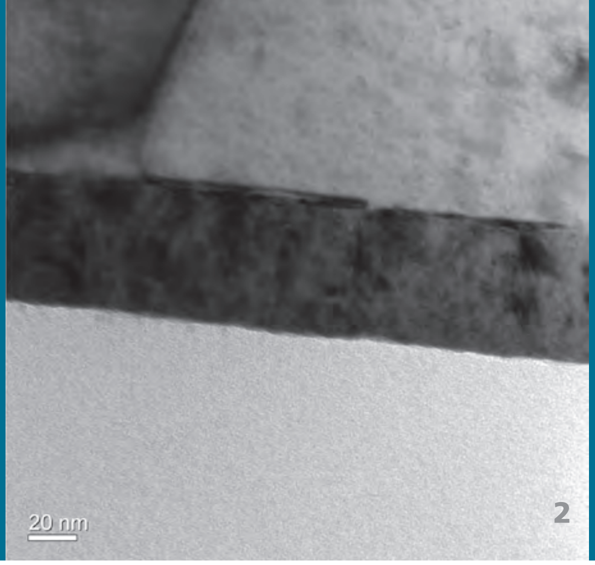

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3

CHARACTERIZATION OF COPPER ALLOYS FOR SELF-FORMING BARRIER APPLICATIONS

Mathias Franz, Ramona Ecke, Christian Kaufmann, Stefan E. Schulz

Introduction

In copper wiring systems the barrier layer plays an important role. One major task of the layer is to prevent any Cu contamination of the dielectric. Recent researches focus on the self-forming barrier (SFB) approach. The main idea of SFBs is to replace the common Ta-based barrier with a copper alloy. The alloying element should form an ultrathin barrier layer at the interface to the SiO_2 layer. However, the barrier formation requires a high-temperature step. In the CuDot project the elements Mn, Ti and Zr were investigated and compared to each other, in order to find the most suitable element for the SFB approach.

Integration scheme for self forming barriers

The SFB integration scheme is displayed in figure 1. Basing on the dual damascene technology, the process starts with a patterned dielectric (a). A thin CuX alloy layer is deposited on top (b) and will be used as seed layer for the deposition of the copper bulk (c). Next, the barrier is formed (d). Therefore the wafer has to be heated up to a sufficient temperature. A high chemical gradient will attract the alloying element and an oxide or silicide layer will be formed. The subsequent CMP will remove the excessive Cu and any alloy-oxide on the surface (e). In comparison to the common integration scheme (f), the SFB is located only at the interface Cu/dielectric. This leads to a lower effective resistance especially in the vias.

Alloy properties

We investigated Mn, Ti and Zr as alloying elements in the concentration range of 2 … 10 at. %. The alloys were deposited by co-sputtering. X-ray diffraction measurements show that all elements are deposited in a solid solution. Even CuZr is deposited in solution although these two elements are not miscible. This is a result of the high cooling rate during the sputtering. All three elements show a linear dependency of concentration to resistance. The CuZr system shows the highest values. During the annealing at 400 °C in N_2/H_2 ambient, the resistance reduces strongly. It can be shown that the Zr segregates and forms the Cu_5Zr phase.

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In Kupferleitbahnsystemen spielt die Barriere eine zunehmend wichtigere Rolle. Im CuDot-Projekt wurde der neue Ansatz der selbstformierenden Barriere untersucht. Hierfür wurden Kupferlegierungen hergestellt, die durch eine Temperaturbehandlung eine stabile Barriere an der Grenzfläche zum Siliziumoxid ausbilden sollen. Die Untersuchungen umfassten die Systeme Cu(Mn), Cu(Ti) und Cu(Zr). Die Proben wurden für 60 min bei 400 °C in einer N_2/H_2 Atmosphäre behandelt. Es konnte gezeigt werden, dass alle Elemente eine Anreichungsschicht an der Grenzfläche zum Dielektrikum ausbilden. Die Stabilität der Barriere wurde mittels der Triangular-Voltage-Sweep Methode untersucht. Diese eignet sich besonders, um geringe Mengen an Kupfer im Dielektrikum nachzuweisen. Es konnte gezeigt werden, dass sich Mn und Ti besonders für selbstformierende Barrieren eignen.

Barrier formation

For the analysis of the barrier formation, we produced a layer stack of SiO_2 (200 nm), alloy (50 nm) and pure Cu (500 nm). The wafers were annealed at 350 °C and 400 °C in N_2/H_2 atmosphere. Initially, the effective resistance of the layer stack was significantly higher than the value of a pure Cu layer. However, with the thermal annealing, we could reach values similar to pure Cu. Especially CuTi shows the best results. The barrier formation process has been investigated with tunnelling electron microscopy (TEM) measurements. Figure 2 shows the as deposited state of an untreated layer stack. The alloy layer can clearly be separated from the pure Cu on top. Figure 3 shows a similar wafer after the annealing step. It can be shown, that each investigated element (Mn, Ti and Zr) will form an enrichment layer on the interface dielectric/alloy. This was proven by energy filtered TEM measurements, which show the element distribution in the analyzed area.

Barrier stability

It is mandatory to prove the barrier stability of the new approach. Therefore, we produced MIS-testing structures which were tested with bias-temperature-stress (BTS) measurements and the triangular-voltage-sweep (TVS) method. It can be shown that a Zr SFB is less stable than a Mn or Ti SFB. Its leakage current is one magnitude higher than the other systems. A Ti-based barrier is slightly better than a Mn SFB.

Conclusion

We could show that all elements are capable to be used as SFB. Mn, Ti and Zr form an enrichment layer during the thermal annealing. Due to barrier stability and effective resistance, Ti seems to be the most suitable element for the SFB approach.

Acknowledgments

This work was supported by the EFRE fund of the European Community and by funding of the Free State of Saxony of the Federal Republic of Germany.
Special thanks to our project partner Infineon Technologies Dresden.

1 *Integration scheme of new SFB approach (a-e) and common interconnect system (f).*

2 *TEM image of untreated alloy/copper stack.*

3 *TEM image of annealed CuTi/Cu-sample with Ti enrichment layer.*

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SMART MEDICAL SYSTEMS

In medical engineering, Fraunhofer ENAS addresses the following topics:

- Diagnostics and monitoring, in particular:
  - Highly integrated lab-on-a-chip solutions for point of care diagnostics
  - Fabry-Pérot interferometer, NIR/MIR MEMS spectrometer
  - Printed batteries for low-cost disposables
- Implants
  - Miniaturized sensors for medical applications
  - Wireless power transmission
  - Biocompatible packaging, inclusively surface modification, nano-imprinting for medical applications
- Reliability of smart systems for medical engineering

Within the 2014 annual report, we present three selected projects. The first one addresses a vertically integrated array-type Mirau-based OCT system for early diagnostics of skin pathologies. Fraunhofer ENAS focuses on the development of multiple wafer bonding technology to realize the high accuracy of the optical system. Moreover, Fraunhofer ENAS is working on biocompatible implant packaging.

The latter addresses the successful advancement of Fabry-Pérot filters. Some types of infrared filters are already commercially available and are fabricated successfully in a 6-inch MEMS wafer-level process, with up to 240 chips per wafer compound. New types demonstrate advanced technologies, e. g. reflectors made of subwavelength gratings, fabricated using nano-imprinting lithography to enhance spectral range, resolution, mechanical stability and process technology.

The third article describes the development of a microfluidic chip for glycated hemoglobin (HbA1c), which is a long-term blood glucose marker currently only available by laboratory testing.

In der Medizintechnik adressiert Fraunhofer ENAS Themen aus den Bereichen:

- Diagnostik und Monitoring, u.a.
  - hochintegrierte Lab-on-a-Chip-Lösungen für die Point of Care Diagnostik
  - Fabry-Pérot-Interferometer (FPI), NIR/MIR-Mikrospiegel-Spektrometer
  - Gedruckte Batterien für low-cost Disposables
- Implantate
  - Miniaturisierte Sensoren für medizintechnische Anwendungen
  - Biokompatible Aufbau- und Verbindungstechnik, einschließlich Oberflächenmodifikation, Nanoimprinting für medizinische Anwendungen
  - Drahtlose Energieversorgung
- Zuverlässigkeit von intelligenten Systemen für die Medizintechnik inklusive Werkstoffcharakterisierung

Für den Jahresbericht 2014 haben wir drei Projekte ausgewählt. Das erste adressiert ein optisches Kohärenztomografiesystem zur Früherkennung von Hautkrebs. Hierfür wurde am Fraunhofer ENAS eine Mehrfach-Waferbondtechnologie speziell für die benötigten hohen Genauigkeiten des optischen Systems entwickelt. Im Bereich des Packaging stehen darüber hinaus die biokompatiblen Aufbau- und Verbindungstechniken für Implantate im Vordergrund der Arbeiten.

Der zweite Artikel adressiert die erfolgreiche Weiterentwicklung der Fabry-Pérot-Filter. Einige Filtertypen werden bereits erfolgreich, mit bis zu 240 Chips pro Waferverbund, in einem 6-Zoll-MEMS-Prozess hergestellt. Neue FPI-Chips zeigen technologische Weiterentwicklungen, wie z.B. die Verwendung von Subwellenlängenstrukturen zur Herstellung von Reflektoren mit Nanoimprintlithographie.

Der dritte Artikel beschreibt die Entwicklung eines mikrofluidischen Chips für glykiertes Hämoglobin HbA1c. Der Blutzuckerlangzeitwert HbA1c kann gegenwärtig nur im Labor getestet werden.

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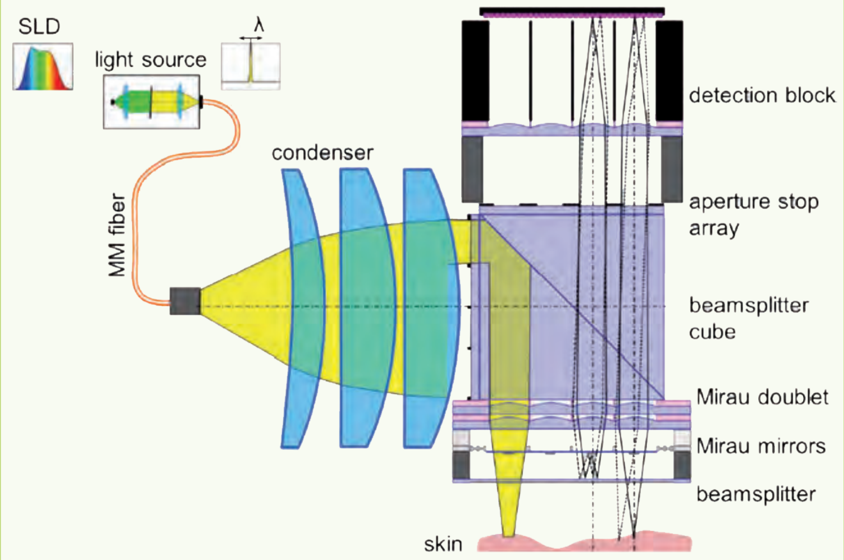

2

VIAMOS – VERTICALLY INTEGRATED ARRAY-TYPE MIRAU-BASED OCT SYSTEM FOR EARLY DIAGNOSTICS OF SKIN PATHOLOGIES

Wei-Shan Wang, Jörg Frömel, Maik Wiemer

Skin cancer is the most commonly diagnosed type of cancer and the chances of successful treatment increase when detected earlier. Therefore, the early diagnosis is essential. Existing Optical Coherence Tomography (OCT) systems, which provide higher resolution and greater detection depth, can perform noninvasive 3D optical biopsies of skin and improve patient's quality of life. Nevertheless, these bulk systems are expensive, only affordable at the hospital and hence not sufficiently employed by physicians or dermatologists as an early diagnosis tool. VIAMOS aims to develop a handheld, low-cost and multifunctional OCT microsystem, which enables a painless and earlier detection of skin pathologies like melanoma and nonmelanoma cancers.

By combining swept-source OCT detection and micro-opto-electromechanical systems (MOEMS) technologies, a miniature, low-cost, portable OCT microsystem, which is 10 times cheaper and 150 times smaller than the conventional commercially available systems, is proposed. The OCT microsystem consists of a tunable light source, objective lens, an array of Mirau interferometers, a beamsplitter cube to superimpose the illumination with the imaging path and an imaging lens for the CCD camera, as shown in figure 1. The incident light beam from a broadband light source is filtered by a tunable Fabry-Pérot interferometer (FPI), collimated and imaged on the skin. The backscattered light from the skin and the light from the reference mirror are imaged into a high-speed camera and form the measurement signal.

A Mirau interferometer, which is a key component of the OCT microsystem, consists of a doublet of array of micro lenses, an array of actuated micro mirror, a focus-adjustment spacer and a beam splitter plate. Batch fabrication of the array-type Mirau interferometers can be achieved through optimized MOEMS process which gathers similar components onto specialized wafers such as Si or glass. 3D packaging technology involving heterogeneous integration plays a crucial role for the integration of MOEMS devices with a minimum of space and low power consumption. A multi-wafer bonding technology combined with electrical connection functionality is utilized for the integration of a micromachined array-type Mirau interferometer proposed in VIAMOS project. This vertical assembly process must meet technical requirements of a Mirau interferometer including alignment tolerance, hermeticity, and high bond strength to ensure reliable movement of the Mirau interferometer. Meanwhile, material and process compatibility are also crucial issues in order not to deteriorate optical performance of microlenses, micro mirrors and beamsplitter.

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Figure 2 shows a SEM image of a 5-stack demonstrator simulating a Mirau interferometer stack. A 200 µm silicon bonded with a 500 µm glass represents a micro lens wafer. The SOI wafer represents an actuated micro mirror. The bottom glass stack consists of 2 glass wafers, representing a spacer and a beam splitter. The higher magnification image shows that an upper glass is bonded with a bottom glass, where aluminum thin layer is deposited. All bonding processes are carried out by anodic bonding and bonding temperature lower than 360 °C. The approach, which adopts vertically-stacked wafers along with electrical connection functionality, provides a space-effective integration of MOEMS device such that the Mirau stack can be further integrated with other components of the OCT microsystem easily.

This work is supported by the collaborative project VIAMOS of the European Commission (FP7-ICT-2011-8, Grant no. 318542).

Hautkrebs gehört zu den am häufigsten detektierten Arten von Krebs; frühzeitige Erkennung verbessert auch hier die Chancen erfolgreicher Heilung. Optische Kohärenztomografie ist eine Möglichkeit zur nichtinvasiven Untersuchung von Haut. Allerdings sind die verfügbaren Systeme groß und so preisintensiv, dass in der Regel nur gut ausgestattete Krankenhäuser darüber verfügen.

Im Projekt VIAMOS ist es Ziel, ein tragbares, preiswertes Analysegerät zu entwickeln, dass zur Frühdiagnose bereits beim Haus- oder Hautarzt eingesetzt werden kann. Durch den Einsatz von mikrooptischen Systemen (MOEMS) soll eine Verkleinerung um den Faktor 150 und eine Verringerung des Preises auf 10 % erreicht werden. Ein solches Analysesystem besteht aus einer durchstimmbaren Lichtquelle, Linsen, einer Matrix von Mirau-Interferometern, einem Strahlteiler und einem Fabry-Pérot-Interferometer (FPI) (Abbildung 1).

Das Kernstück des Tomografiesystems ist das Mirau-Interferometer. Es wird mittels Mikrotechnologie hergestellt und ist damit extrem miniaturisiert im Vergleich zu konventionellen Geräten. Eine Doppellinsenmatrix, eine Mikrospiegelmatrix, ein Abstandshalter zur Einstellung des optischen Fokus und ein Strahlteiler werden als Komponenten auf Waferebene miteinander als komplexer Stapel gefügt. Eine Mehrfach-Waferbondtechnologie wurde speziell für die benötigten hohen Genauigkeiten des optischen Systems entwickelt. In Abbildung 2 ist ein solcher gefügter Stapel aus fünf verschieden Wafern im Querschnitt gezeigt.
Die vorgestellten Ergebnisse entstanden im Rahmen eines Kooperationsprojektes, gefördert von der Europäischen Kommission (FP7-ICT-2011-8, Grant no. 318542).

1 *Schematic of VIAMOS OCT microsystem.*

2 *Cross-sectional SEM image of a 5 bonding stack simulating a Mirau interferometer.*

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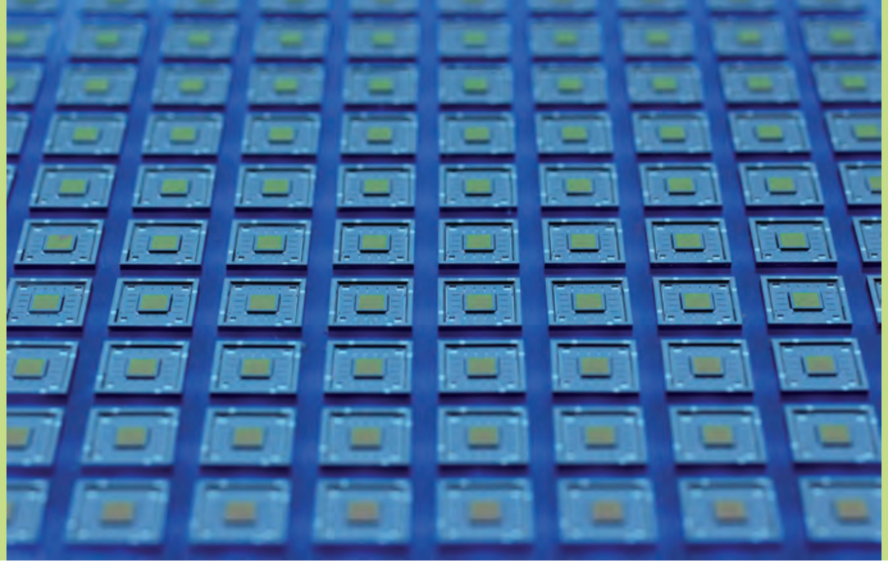

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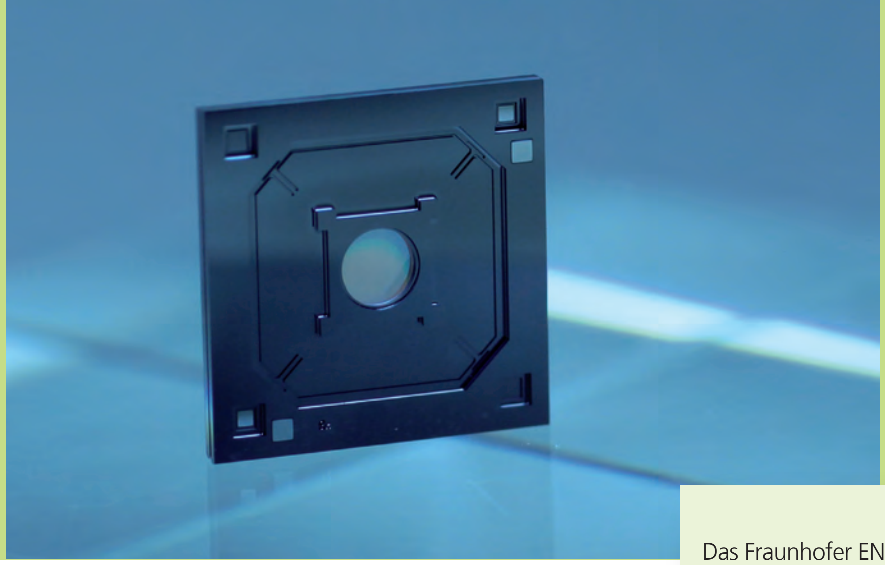

TUNABLE BAND-PASS FILTERS FOR INFRARED LIGHT

Steffen Kurth, Karla Hiller, Marco Meinig, Christian Helke, Mario Seifert, Jan Seiler, Martin Ebermann, Norbert Neumann**
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Fraunhofer ENAS develops together with its partners Technische Universität Chemnitz/Center for Microtechnologies and InfraTec GmbH electrically tunable band-pass filters for infrared light. The development is part of several funded projects (MIDAS[1], SIRKO[2], NanoRef[3], Nano3pt[4]) as well as contracts with InfraTec GmbH. Some types of the infrared filters are commercially available already and are fabricated successfully in a 6-inch MEMS wafer-level process, with up to 240 chips per wafer compound. New types demonstrate advanced technologies, e.g. reflectors made of subwavelength gratings, fabricated with nano-imprint lithography, to enhance spectral range, resolution, mechanical stability and process technology.

The target application in most of the projects is spectral gas analysis in medical and technical areas. In medical diagnostics especially the monitoring of carbon dioxide and anesthetics, such as halogenated ethers and nitrous oxide, in respiratory air are of strong interest. In general, the analysis is done by measuring the infrared absorption spectrum of the gases. Many medical and technical gases have strong absorption bands in the infrared spectral range especially between 3 µm and 12 µm wavelength. In a common spectrometer set-up, the band-pass filters are used as wavelength selecting element in front of a broadband infrared detector. The gas is placed in a sample cell between an infrared emitter and the spectrometer set-up. The absorption spectrum of the gas is measured in transmittance by stepwise tuning the infrared filter through the relevant spectral range.

InfraTec GmbH integrates the components of the spectrometer set-up in a tiny TO-8 package. They are commercially available for different spectral ranges, as well as in single-band and dual-band configurations. A dual-band configuration uses two passbands of the infrared filter and allows for the simultaneous measurement in these two spectral ranges. This is achieved by adding a dichroic beam splitter and a second broadband infrared detector to the spectrometer set-up. The dual-band type still fits in a TO-8 package, with only a small increase in the sensor height. The MEMS micro-spectrometers have many advantages, e.g. small size, small prize, small weight and mechanical robustness and are therefore a very promising enhancement of existing spectrometer solutions.

Technically, the tunable infrared filters are tiny Fabry-Pérot interferometers (FPI). They consist of two mirrors that build an optical resonator in between. To obtain an excellent spectral performance the surfaces of the mirrors have to be smooth and highly reflective and the mirrors have to be aligned parallel to each other very precisely. The transmittance spectrum of the FPI shows a passband at each interference order and strong blocking of the radiation in between. The passbands can be shifted by varying the distance between the mirrors. The spectral range between two adjacent passbands is call the free spectral range of the FPI and is the maximum tuning range of the infrared filter.

The filters are fabricated in a sophisticated MEMS wafer-level process. They consist of two silicon wafers, which are bonded together by either silicon fusion bonding or an intermediate SU-8 polymer layer. The optical resonator is built between the bonded wafers. The mirrors are deposited before bonding on the inner sides of the wafers in very precisely wet-etched cavities. On the other side of the wafers, an anti-reflective coating is deposited. At least one wafer of a compound consists of moveable mirror carriers that are actuated electrostatically to vary the distance between the mirrors.

Different types of the infrared filters cover the spectral range between 3 µm and 11 µm. They have an optical aperture of up to 2 mm x 2 mm. The peak transmittance is up to 90 % and the full width at half maximum can be as small as 20 nm. The tuning voltage depends on the spectral range, but is below 50 V for many types. The chips have a size of 7 mm x 7 mm x 0.6 mm.

Das Fraunhofer ENAS entwickelt zusammen mit seinen Partnern, dem Zentrum für Mikrotechnologien der Technische Universität Chemnitz und der InfraTec GmbH, elektrisch abstimmbare Bandpassfilter für den infraroten Spektralbereich. Die Entwicklungen wurden in verschiedenen Projekten (MIDAS[1], SIRKO[2], NanoRef[3], Nano3pt[4]) öffentlich gefördert sowie durch die Firma InfraTec GmbH. Einige Filtertypen werden bereits erfolgreich, mit bis zu 240 Chips pro Waferverbund, in einem 6-Zoll-MEMS-Prozess hergestellt. Neue FPI-Chips zeigen technologische Weiterentwicklungen, wie z.B. die Verwendung von Subwellenlängenstrukturen zur Herstellung von Reflektoren mit Nanoimprintlithographie. Die InfraTec GmbH integriert die Filter mit zusätzlichen optischen Komponenten und Infrarotdetektoren in kompakte TO-8 Gehäuse. Diese Module sind leistungsfähige Mikrospektrometer, wobei das abstimmbare Infrarotfilter als wellenlängenselektives Element wirkt. Verschiedene Typen des Infrarotfilters decken den Spektralbereich von 3 µm bis 11 µm Wellenlänge ab. Sie arbeiten nach dem physikalischen Prinzip des Fabry-Pérot-Interferometers. Die Filter haben eine optische Apertur von 2 mm x 2 mm. Die Maximaltransmission beträgt bis zu 90 % und die Bandbreite (FWHM) bis zu 20 nm. Die Durchstimmspannung hängt vom gewählten Spektralbereich ab, liegt jedoch für viele Typen unter 50 V. Die Chips haben eine Größe von 7 mm x 7 mm x 0,6 mm.

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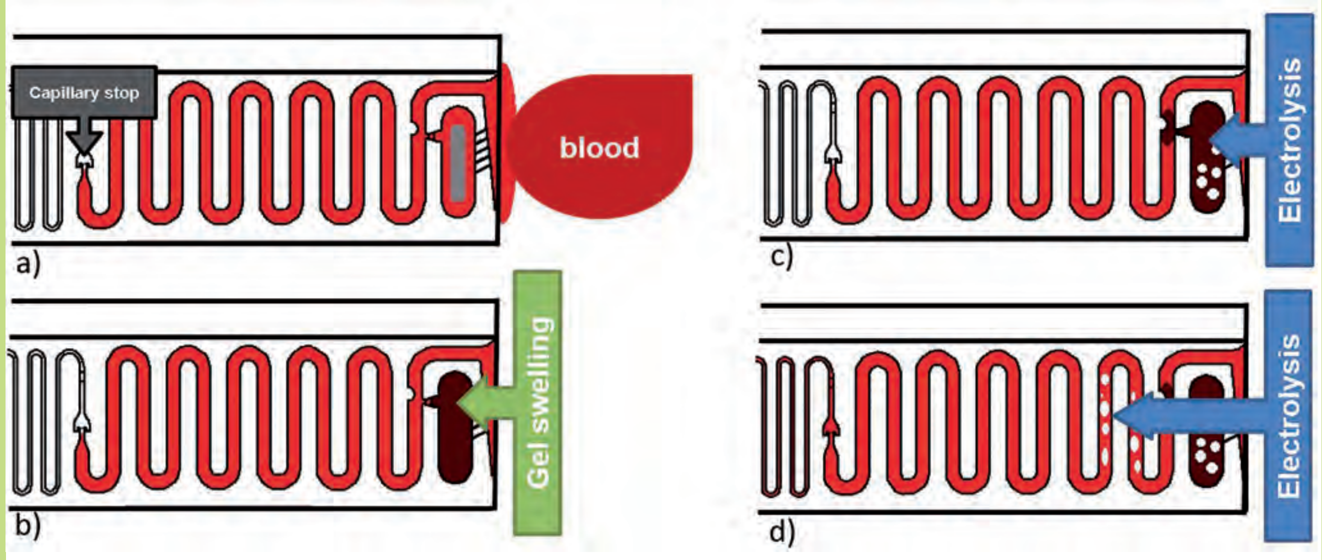
1 *Photograph of FPIs with distributed Bragg reflectors.*
2 *Photograph of FPI with subwavelength grating reflectors.*



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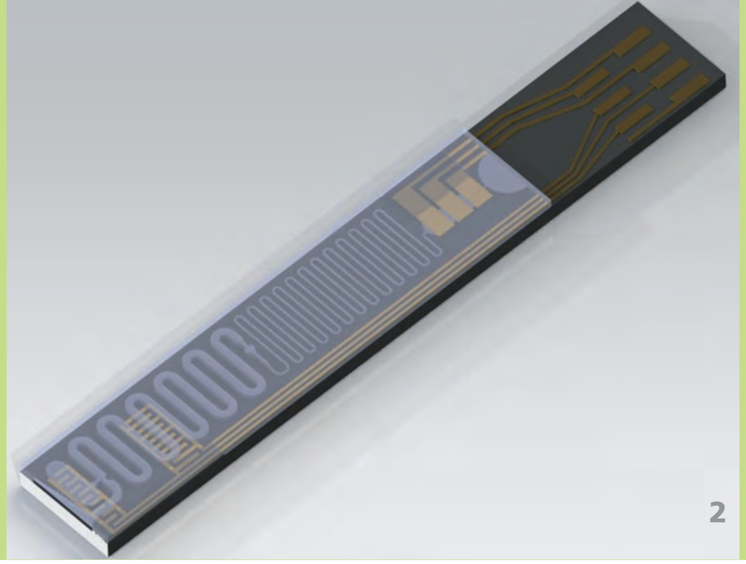

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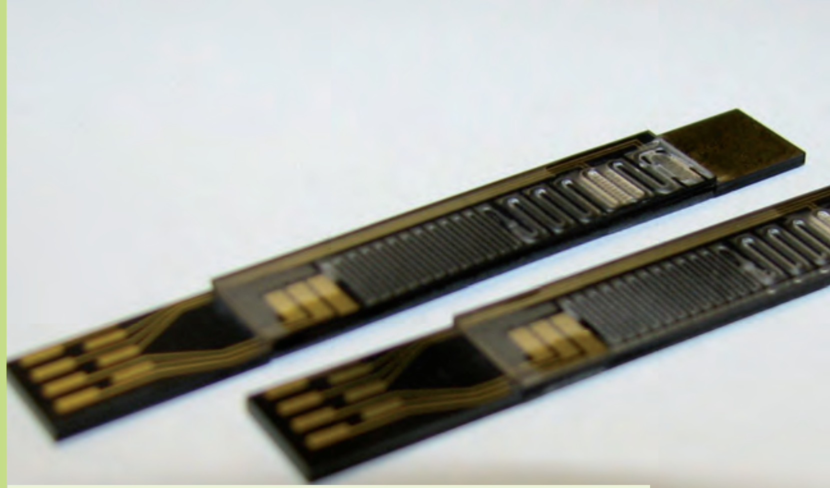

3

CAPILLARY MICROFLUIDIC CHIP WITH INTEGRATED PUMP AND VALVE ACTUATOR

Andreas Morschhauser, Allyn Große, Sascha Geidel, Tom Enderlein, Jörg Nestler, Thomas Otto, Thomas Gessner

Glycated Hemoglobin (HbA1c) is a long-term blood glucose marker currently only available by laboratory testing. Main hurdle for point-of-care testing of HbA1c is the necessary on-chip sample preparation. One limiting factor is the lack of miniaturized, time-controlled liquid actuation functionalities. Thus, an electrochemical pumping has been used for the required flow control. In contrast to previous works [1] the sample is directly used as working liquid for pumping and valving. Differently to e.g. [2] a novel gel-based check valve approach is employed to avoid undesired liquid movement towards the inlet of the chip. This method results in a miniaturization of the chip design and sample volume, the combination of passive and active microfluidics and the elimination of external handling steps and additional reagents.

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Concept: Dry hydrogel valving approach

The intended microfluidic sequence to be performed by the chip includes capillary sample uptake and the pumping of an exactly defined and minimized volume (5 µl) into a preset analyzing channel (Fig. 1). After capillary filling of the inlet channel and the valve reservoir the dried super absorber swells due to contact with the sample and forms a gel. Subsequently the gel (swollen super absorber) is pushed into the channel by electrolysis to form a check valve at an adjustable time.
In the next step the sample is further pushed towards a measuring chamber by a second electrolysis actuator which is placed downward in the inlet channel. The gel valve avoids liquid movement towards the inlet. The described actuation concept was transformed by a layout jointly developed by Fraunhofer ENAS and Senslab GmbH.

Fabrication of the microfluidic chip

The polymer chip consists of a transparent, hot embossed channel layer (polycarbonate) and a metalized bottom layer (gold on polycarbonate) for electrode integration. The chip dimensions are 39 mm x 6 mm. The fabrication steps include PVD-coating, laser structuring of the electrodes, hot embossing and laser welding. Gold as the electrode material was deposited on a black polycarbonate foil by PVD. Afterwards, the electrodes were micro structured by laser ablation. The microchannel substrate was fabricated by hot embossing by our partner institute Fraunhofer IWU [3].
Before joining the hot embossed part and the electrode part a small amount of hydrogel was applied inside the valve reservoir. The gel was subsequently dried to obtain a well-localized super absorbing material for swelling during usage.
As final step laser contour welding was employed to join the two layers. Therefore, a continuous 20 W IR-fiber laser with attached scanner system and a spot size of 50 µm was used. The thermal influence of the laser beam is limited to the welded structures with only minor thermal effects in the surrounding material. This allows the integration of a (temperature sensitive) biochemical coating before joining. Only for the sealing of the electrode areas small adhesive tapes were used, since laser welding would result in the destruction of the electrodes.

Results

The whole process flow was tested with distilled water and human capillary blood as sample medium.
The experiments showed that both liquids are useable for gel formation. If distilled water is used, however, a small amount of super absorber is sufficient for swelling and building up a valve. With growing number of ions in the medium (such as for blood) the amount of super absorber has to be increased.

Conclusion and acknowledgment

A microfluidic chip combining capillary and active flow control has been developed. The chip uses a novel approach for electrochemical pumps based on hydrogel swelling and electrolysis. Inlet sealing is carried out "on-chip" by an innovative valving concept. The functionality of the novel approach has been demonstrated for distilled water and capillary whole blood.
This presented work was performed in the project GlykHbLab (FKZ V4MOD023) funded by the German Federal Ministry of Education and Research.

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Am Beispiel eines Technologiedemonstrators für die Detektion von glykiertem Hämoglobin wurde eine mikrofluidische Lösung entwickelt, welche neben einer kapillaren Befüllung von Kanälen auch aktive Ventile sowie einen aktiven, zeitgesteuerten Probentransport erlaubt. Dabei wird zunächst ein Messkanal bis zu einem Kapillarstopp mit Probe gefüllt. Die flüssige Probe dient gleichzeitig dazu, einen Superabsorber anschwellen zu lassen. Das entstandene Gel dient nun als Rückschlagventil, so dass der kapillar-befüllte Kanal eingangsseitig verschlossen wird. In der Folge kann die Probe nun zeitgesteuert weiter transportiert werden, indem mittels Elektrolyse in der Probenflüssigkeit ein Gasdruck erzeugt wird. Um die Probe nicht zu verfälschen, geschieht dieser Vorgang in einem Kanalabschnitt, dessen Inhalt später nicht den Messbereich erreicht.

Das Fraunhofer ENAS forscht bereits seit etwa zehn Jahren an integrierbaren Aktoren, wie sie z.B. für Systeme in der Vorort-Diagnostik zum Einsatz kommen. Ein wesentlicher Schwerpunkt der Aktivitäten liegt dabei auf Einwegsystemen.

1 *Schematics of the working principle. (a) capillary filling, (b) hydrogel swelling, (c) check valve formation, (d) pumping.*

2 *CAD model of the chip.*

3 *Chips fabricated by laser ablation, laser welding, dispensing and hot embossing.*


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SMART POWER

In the Smart Power chapter, Fraunhofer ENAS addresses the aspects of empowering systems, reliability investigations of new materials for energy systems as well as sensors for autonomous, energy-self-sufficient sensor networks for optimizing the capacity utilization of the power lines:

- Energy supply of components and systems
  - Thermoelectric materials
  - Development and manufacturing of printed batteries for smart systems
  - Wireless energy supply using SUPA technology
  - Reduction of the energy consumption of smart systems
- Power line monitoring (100 kV, 220 kV, 380 kV)
- Reliability of materials, components and systems

Reliability is a hot topic for all applications. The application of power modules in future smart mobility and energy solutions requires new interconnection technologies. Fraunhofer ENAS focuses on the thermo-mechanical reliability risks and establishes design rules.

In 2013, we reported on printed batteries, SUPA technology and increased energy efficiency of sensor nodes. In the 2014 annual report, we focus on thermoelectric materials. In cooperation with the World Premier International Research Center Initiative Advanced Institute for Materials Research (WPI-AIMR) at Tohoku University Sendai, metallic glass nanowires are tested for power generation devices. High-temperature-stable and long-term-stable thermoelectric generators with the highest-possible efficiency for use in motor vehicle exhaust are developed in cooperation with the University of Paderborn.

The ASTROSE® system, the autonomous and energy-self-sufficient sensor network for optimizing the capacity utilization of the power lines has been running in an extended pilot test in the Harz Mountains since September 2014. Therefore, the power line has been equipped with 60 sensor nodes. The results will be available in 2015.

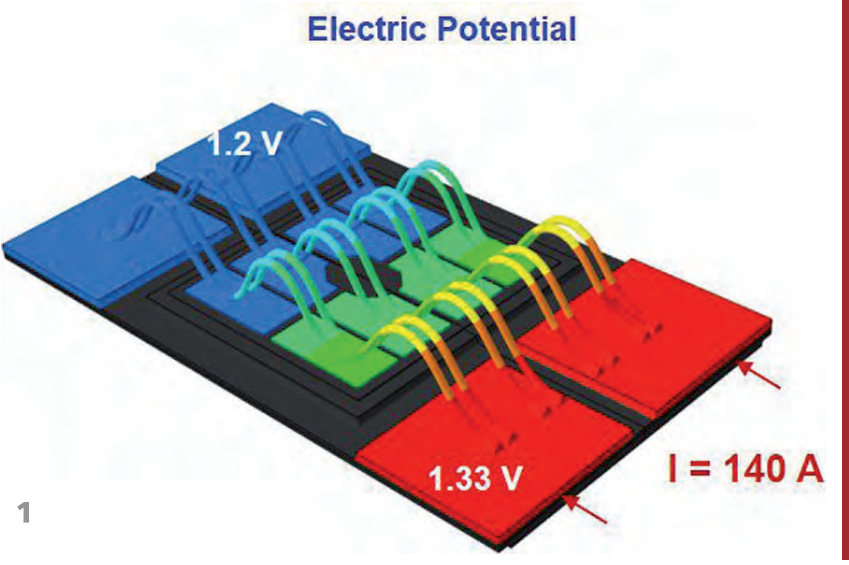
Im Bereich Smart Power adressiert Fraunhofer ENAS Aspekte der Energieversorgung von Systemen, Zuverlässigkeitsuntersuchungen beim Einsatz neuer Materialien für Energiesysteme sowie den Einsatz von Sensorik in autonomen Sensornetzwerken für die Optimierung der Kapazitätsauslastung von Hochspannungsleitungen:

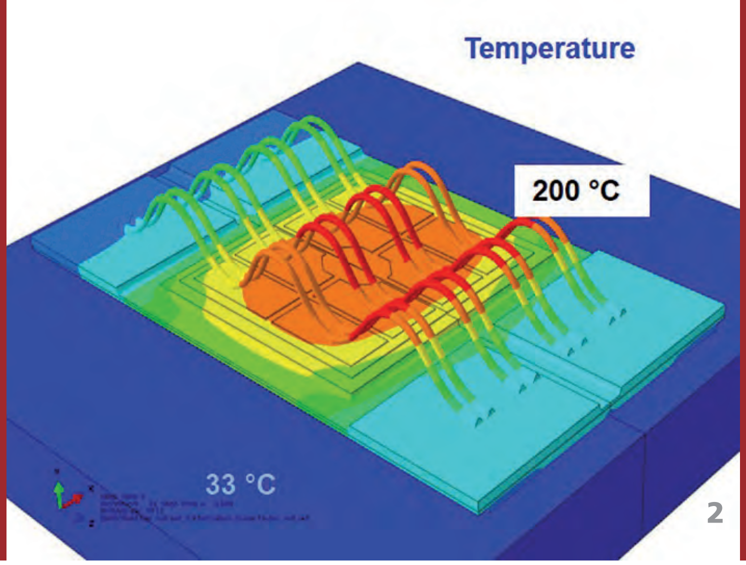
- Energieversorgung von Komponenten und Systemen
  - Thermoelektrische Materialien
  - Drucktechnische Herstellung von Batterien für intelligente Systeme
  - Drahtlose Energie- und Datenübertragung mittels SUPA-Technologie
  - Reduzierung des Energieverbrauchs intelligenter Systeme
- Freileitungsmonitoring von Stromnetzen (100 kV, 220 kV, 380 kV)
- Zuverlässigkeit von Materialien, Komponenten und Systemen

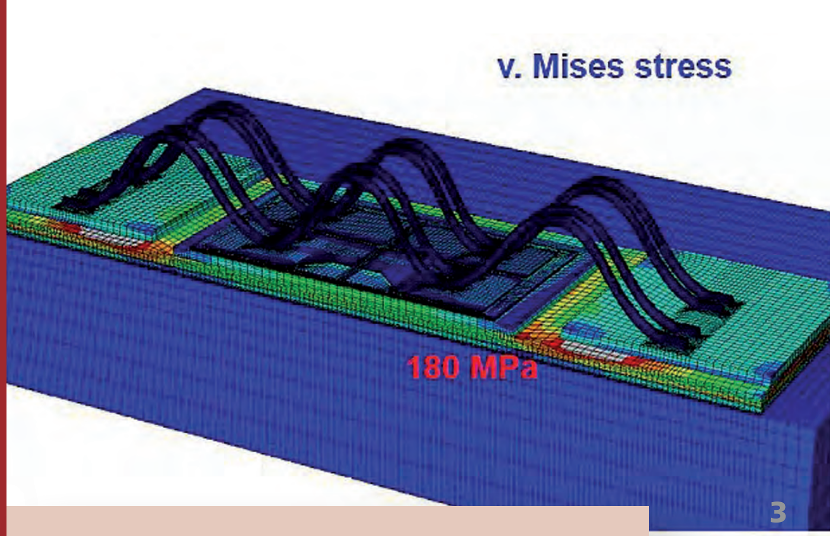
Der Einsatz von Leistungselektronikmodulen erfordert neue Verbindungstechnologien für künftige intelligente Mobilitäts- und Energiesysteme. Im Bereich Zuverlässigkeit beschäftigt sich Fraunhofer ENAS mit den Ausfallrisiken und Design-Regeln.

Nachdem 2013 ausführlich über die gedruckte Batterie, die SUPA-Technologie und die Erhöhung der Energieeffizienz der Sensorknoten berichtet wurde, stehen im Jahresbericht 2014 thermoelektrische Materialien im Vordergrund der Betrachtungen. Gemeinsam mit dem World Premier International Research Center Initiative Advanced Institute for Materials Research (WPI-AIMR) der Tohoku Universität Sendai wird der Einsatz von Nanodrähten aus metallischem Glas für Thermogeneratoren getestet. In Kooperation mit der Universität Paderborn werden hocheffiziente, hochtemperaturtaugliche und zeitstabile Thermogeneratoren für den Einsatz im Abgasstrang von Kraftfahrzeugen entwickelt.

Das ASTROSE®-System zum Freileitungsmonitoring befindet sich mit 60 Sensorknoten seit September 2014 in einem umfangreichen Pilotversuch im Harz. Die Ergebnisse liegen in 2015 vor.







‘DESIGN FOR RELIABILITY’ IN POWER ELECTRONICS WITH NEW INTERCONNECTION TECHNOLOGIES FOR FUTURE SMART MOBILITY AND SMART ENERGY SOLUTIONS

Rainer Dudek, Ralf Döring

New solutions for use of electrical energy require increased power density for energy efficiency

The increase in the permissible operating peak temperatures is an important prerequisite for increasing the efficiency in power electronics modules and thus the energy efficiency of the electric drives and power steering. However, for use of power electronic components it may come to local peak temperatures above 175 °C, which can no longer be controlled with soft solders. New materials for interconnects are required. Silver sintering is a promising new technology for interconnection purposes in power applications which allows high operating temperatures of the interconnects. This type of interconnection technology can be applied already for silicon semiconductors; however, if new high-temperature resistant semiconductors like SiC and GaN come into use there will be an absolute need for these interconnects. Development of these interconnection technologies and experimental and theoretical studies on their reliability were subjects of the BMBF-funded project ”PROPOWER”. In the department MMC, the focus was on theoretical analysis of thermo-mechanical reliability risks that have been carried out using the finite element method (FEM).

Use of new materials for electronic systems and their interconnections means knowledge of new failure risk and design rules

Thermally induced stress due to thermal mismatch between the chips stacked between metallic and ceramic layers is generally the source for thermo-mechanical failure. Introduction of a new interconnect material means at the same time introduction of a new constitutive behavior and new failure modes. As the material stiffness increases, the decoupling effect of compliant solder layers reduces and intrinsic mechanical stresses increase in the whole power stack. This leads on one hand to less low cycle fatigue in the interconnect, as plastic dissipation is reduced, but to higher failure risks like brittle cracking and sub-critical crack growth. However, if early brittle failure can be avoided by appropriate designs, the new interconnection technology allows an increase in fatigue reliability of several hundred percent.

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Optimal functional, mechanical, electrical and thermal design becomes key for competitive products

Two kinds of temperature loadings are essential for power electronic systems: passive thermal cycling, reflecting environmental temperature changes and active power cycling, i.e. power on/off. Both, passive and active thermal cycling, were investigated for power IGBT on DBC substrate with copper bonding technology. FE-analyses revealed that the stress loadings are different for passive and active cycling and hence, different failure modes have to be expected.

Active thermal cycling is most relevant for use condition in field. Different power cycling conditions were studied by FEA to understand the transient stress regime in the assembly. To obtain a realistic result comparable to testing, in particular to include the heat dissipation along the current path through the stack, fully coupled electrical, thermal and mechanical analyses were made.

Only these numerical multi-field simulations based on sophisticated material- and damage modeling can make the goal of “first time right” a reality during the design phase

Starting from the electrical model with voltage distribution in the metallization and bonding wires, as exemplified in figure 1, the current distribution is calculated, which allows coupled calculations of the transient temperature distributions at each state of the active cycle, as shown for the end of an active cycle in figure 2. In the electric model switching losses and conduction and component characteristics, which result in Joule heating, are considered.

Coupling of the transient temperature fields to mechanical stress simulations are performed after, an example given in figure 3.

Based on this complex theoretical framework simulation results are validated by testing in order to achieve trustworthy thermo-mechanical reliability predictions. These highest standards allow the link to establish design rules for the new technology.

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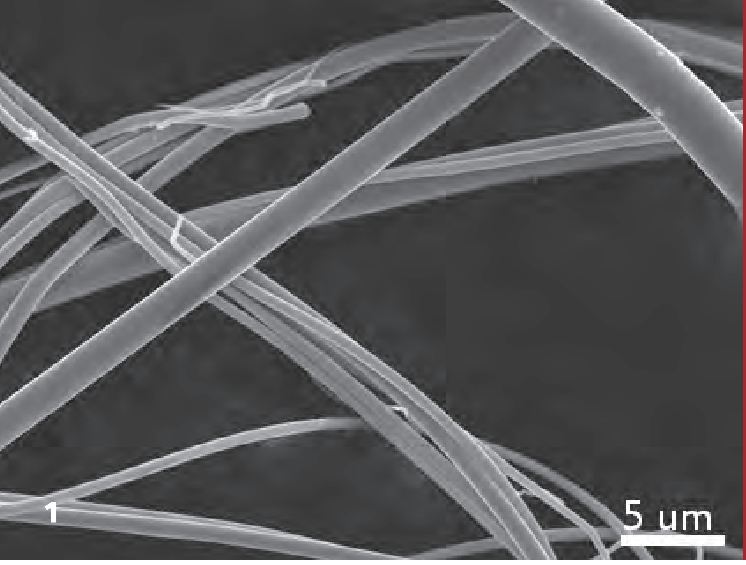
Die Erhöhung der zulässigen Betriebsspitzentemperaturen ist eine wichtige Voraussetzung für die Erhöhung der Effizienz der Leistungselektronik-Module und damit die Energieeffizienz der elektrischen Antriebe und Energiesysteme. Dabei kann es zu lokalen Spitzentemperaturen über 175 °C kommen, die nicht mehr mit Weichloten zu beherrschen sind. Diese Tendenz wird verstärkt durch den Einsatz neuer hochtemperaturfester Halbleitermaterialien wie SiN und GaN. Es machen sich daher neue Materialien und Verfahren der Verbindungstechnologie erforderlich, wie beispielsweise das Sintern von Silber.

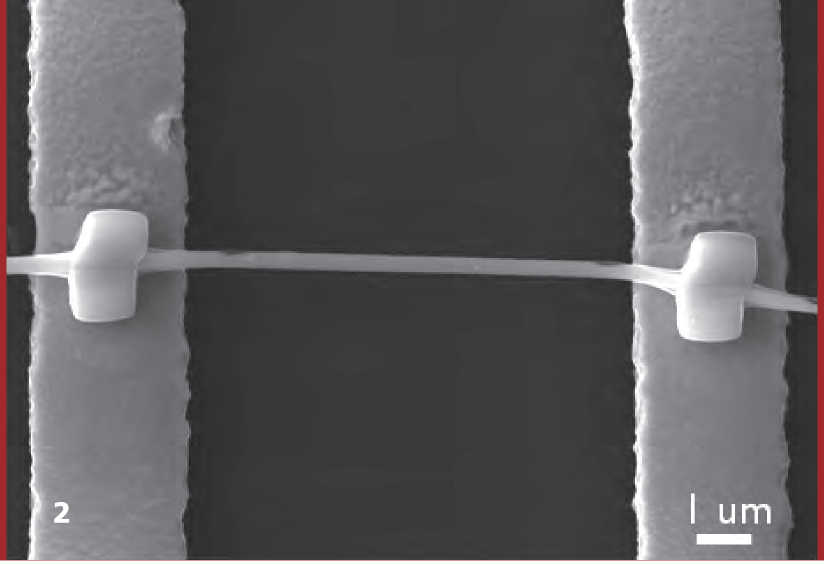
Der Einsatz neuer Materialien für elektronische Systeme und ihre Verbindungen bedeutet aber auch, dass Kenntnisse über neue Ausfallrisiken und Design-Regeln erforderlich werden. Zu dieser Thematik wurden im Projekt „PROPOWER“ sowohl experimentelle als auch theoretische Untersuchungen angestellt. In der Abteilung MMC lag der Fokus dabei auf theoretischen Analysen von thermo-mechanischen Zuverlässigkeitsrisiken, die mit Hilfe der Finiten-Elemente-Methode (FEM) durchgeführt wurden. Es zeigte sich, dass die neuen Werkstoffkombinationen ein verändertes Schädigungsverhalten zeigen, wobei gegenüber den klassischen Lösungen die Betriebsfestigkeit um ein vielfaches erhöht werden kann. Allerdings bergen die steiferen Verbunde bisher nicht vorhandene Risiken des Sprödbruchs. Unter Beachtung der starke Verkopplung des Multi-Materialsystems wurden in der FEM-Modellierung elektro-thermisch-mechanisch gekoppelte Verfahren entwickelt, die es erlauben, ausgehend von einem elektrischen Modell mit gekoppelte Berechnungen der transienten Temperaturverteilungen in jedem Zustand des aktiven Zyklus die mechanischen Beanspruchungen zu bestimmen und in Verbindung mit Testergebnissen auch zu bewerten.

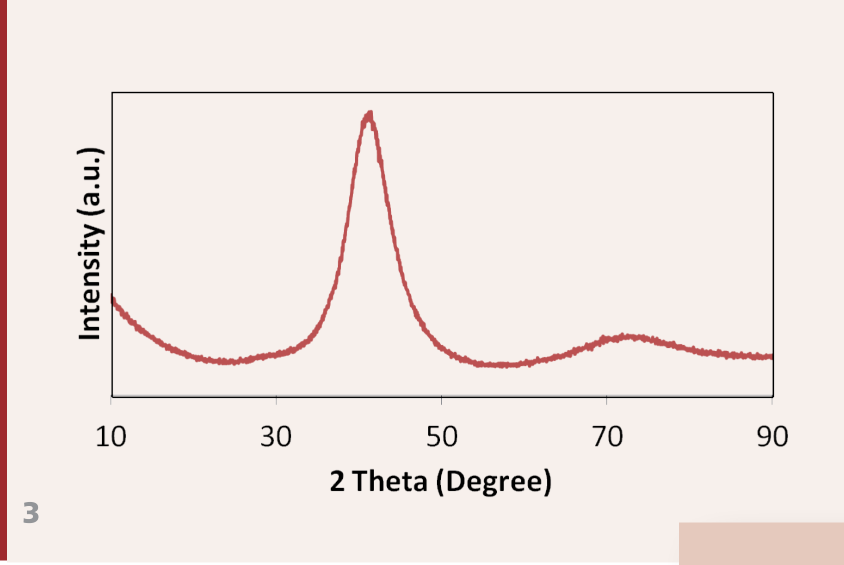
1 *Electrical potential distribution on module during power on state status.*

2 *Temperature distribution caused by electrical load after power on for 3 s.*

3 *Mechanical stress as a result of temperature driven deformation at power on.*







METALLIC GLASS NANOWIRES FOR POWER GENERATION DEVICES

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Approximately 70 percent of the total primary energy used in automobiles and factories is basically wasted. However, the possibilities for reclamation are generally limited because the sources of that waste heat are comparatively small and widely dispersed. High-efficiency thermoelectric materials are therefore being developed and the use of one-dimensional nanostructures to enhance thermoelectric performance is gaining interest.

The specification of high-efficiency thermoelectric materials for power-generation devices

Thermoelectric (TE) materials with high efficiency are important for power-generation devices that could potentially convert waste heat energy from the radiator and exhaust system to electricity based on Seebeck effect. Their efficiency is determined by thermoelectric figure of merit of their material components ZT

$$ZT= S^2T/ \rho k$$

Where S is the Seebeck coefficient, ρ and k are electrical resistivity and thermal conductivity, and T is temperature.

Therefore, the best thermoelectric materials would exhibit phonon-glass and electron-crystal characteristics that have the electrical properties of a crystalline material and the thermal properties of an amorphous or glass-like material.

Why metallic glass nanowire?

The most widely used and commercially available thermoelectric materials are bulk Bi_2Te_3 and its alloys with Pb, Ag, Sb, Se or Cs,… which have $ZT \approx 1$. There also exists a so-called metallic glass (MG) which is amorphous alloy with metallic characteristics. Thermal conductivity and electrical resistivity of bulk MG such as Zr-Al-Ni-Cu, Al-Ni-Y-Co and Pd-Ni-Cu-P were reported in literatures [1], [2], [3]. From this data it seems possible to use them for thermoelectric power generation with high figure of merit.

In addition, nanostructure of materials could significantly improve the figure of merit of TE materials since more significant decrease of thermal conductivity than electrical conductivity could be achieved. Therefore, in an attempt to get high efficiency thermoelectric materials with high ZT, nanostructure of metallic glasses were prepared and characterized.

The metallic glass nanowire device fabrication and main results

Various metallic glasses nanowires containing palladium or zirconium were prepared by gas atomization. Figure 1 shows a scanning electron microscopy (SEM) image of Pd-MG nanowires which exhibits smooth surfaces with various diameters within the range of 50 – 2000 nm. An amorphous structure of these nanowires was confirmed by X-ray Diffraction (XRD). Indeed, the XRD pattern obtained from nanowires consists only of broad halo peaks, as shown in figure 2.

„Bislang gehen durch ineffektive Prozesse bei der Energieumwandlung, in der Produktion und in der Endnutzung Unmengen an Energie ungenutzt verloren. Weltweit gesehen bleiben rund zwei Drittel der Primärenergie auf der Strecke.“[4] Neben verfahrenstechnischen Entwicklungen wird derzeit an neuen Materialien geforscht.

Bewertet man z.B. die Energieeffizienz von Kraftfahrzeugen oder Fabriken, muss heutzutage konstatiert werden, dass ungefähr 70 Prozent der Primärenergie im Wesentlichen in Wärme umgewandelt wird. Die Möglichkeiten der Rückgewinnung sind begrenzt auf Grund der vielfältigen Ursachen für diese ungenutzte Wärme. Ein Lösungsansatz ist die Entwicklung hocheffizienter Materialien für thermoelektrische Energiegeneratoren. Von steigendem Interesse ist der Einsatz von eindimensionalen Nanostrukturen zur Steigerung der thermoelektrischen Leistungsfähigkeit.

In order to measure the thermal and thermoelectric properties of a single nanowires, a microfabricated device with a direct heating method as well as suspended platinum nanofilm sensors were prepared. As shown in figure 3, a nanowire with desired diameter can be placed between the contact pads by using a focus ion beam technique (FIB). The measurement results are already very promising in terms of scalability and thermoelectric performance. Here, we will further optimize device design, fabrication processes and improve the measurement method for the physical and thermoelectric properties investigation of various amorphous metallic glasses and nanowire diameters.

Acknowledgments

This work is performed in collaboration with Professor Koji S. Nakayama's group in WPI-AIMR and researchers in Fraunhofer ENAS through Fraunhofer Project Center in Tohoku University, Japan.

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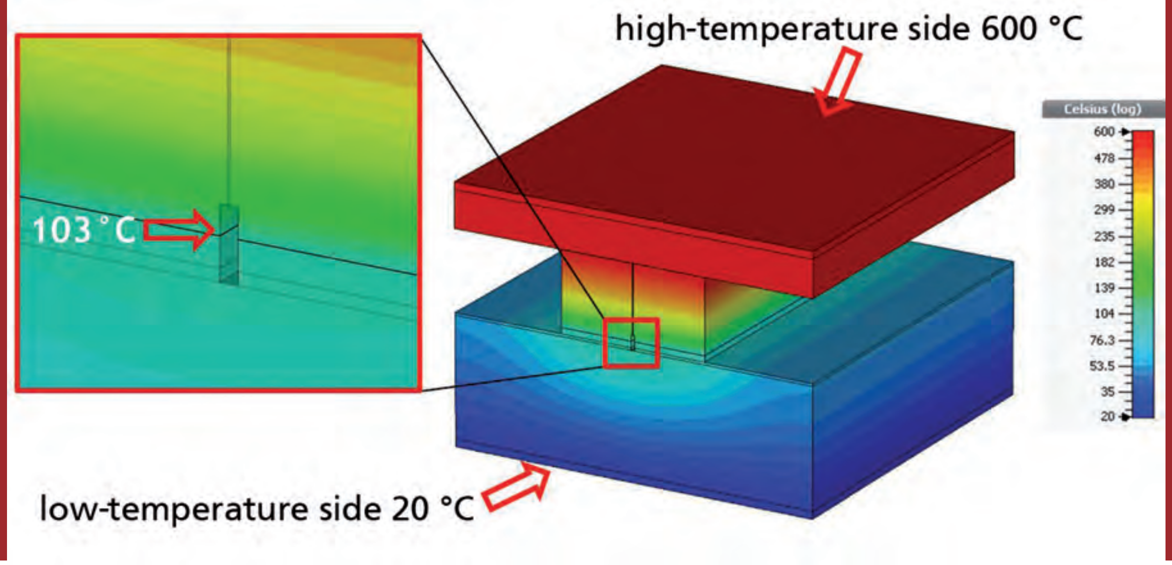
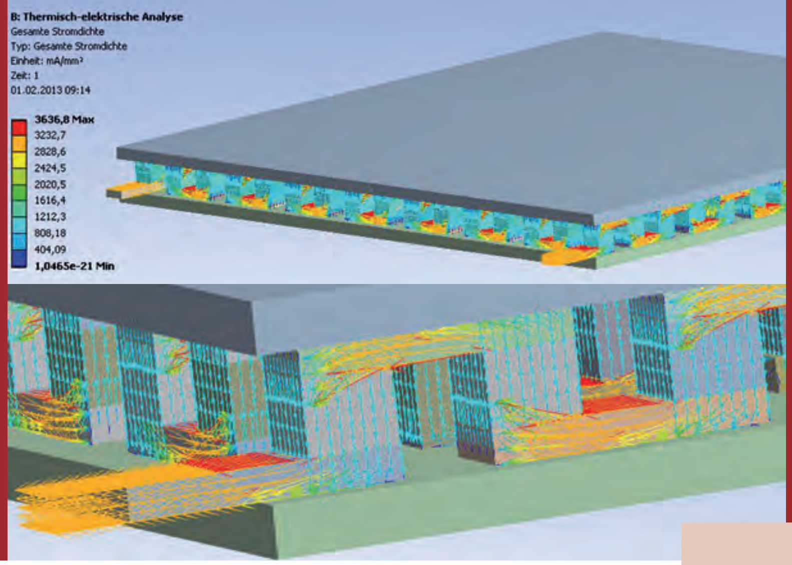
1 SEM image shows the Pd-MG wires of various diameters.

2 SEM image of a Pd-based nanowire of 250 nm-diameter placed between the two contact pads using FIB technique.

3 XRD patterns of the nanofiber show a broad halo peak only.



1 *Temperature distribution in the TEG pairs of legs with a carrier plate of 1.6 mm* Al_2O_3*.*



2 *Current density of TEG 127-200-24 (with detailed view below).*

MODELING METHODS FOR THE PRACTICAL SIMULATION AND OPTIMIZATION OF HIGH-TEMPERATURE THERMOGENERATORS

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The aim of the developed technology is a high-temperature stable and long-term stable thermoelectric generator (TEG) with the highest possible efficiency for use in the exhaust system of motor vehicles. Due to the limited temperature stability of the materials, especially on the high-temperature side, such thermoelectric generators are not available today. Therefore, from the perspective of research, novel materials and compound structures had been developed by the project partner University of Paderborn, while the Fraunhofer ENAS developed a thermoelectrical model capable to simulate continuously the thermal and electrical behaviour of the developed modules. This simulative approach is essential for the success of this work and an early prediction of the efficiency and energy savings of the TEG system is made possible.

In the first approach different silicon thermal legs with different doping were alloyed on a thermally conductive insulator. Even if their efficiency is not optimal, the resulting thermoelectric generators have an extremely high thermal stability up to 1000 K and thus permit initial application tests under extreme thermal conditions. Compared to solder joints, a significant improvement in the degradation at higher temperatures as well as temperature change operations is achieved.

In further developments, the efficiency of the generators was increased considerably by replacing the Si thermocouples with alternative alloys.

In parallel to the material investigations, an analysis of the available simulation softwares with regard to the ability of coupled thermal/electrical simulations was done and conducted to the choice of ANSYS and CST. Dedicated methods have been developed for both tools for modeling and optimization, which allows performing simulations and parameter studies within a reasonable time.

Various materials and structures of thermal generators were modelled, simulated and evaluated. The results of the studies were exemplary verified by measurements on real structures and showed a sensitive matching. Comparison of the results of the two simulators ANSYS and CST has shown that the results of both tools are almost identical. Nevertheless, due to its focus on the solution of electrical and thermal field problems and its associated lower discretization, the CST platform is usually quicker.

Parameter variations (like leg height sweeping) have shown that rapid optimization of geometrical parameters through simulations is possible, depicting the influence of different thermal materials on the optimal leg height. It was showed that, by using iron silicide instead of silicon, the domain of the highest delivered power stays below the currently producible physical dimensions.

Finally, a methodology for optimal adjustment of the TEG designs has been described for different environmental conditions. It has been shown that it is not giving an optimal design for a TEG with maximum efficiency, but that each TEG must be tailored to the specific application.

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Aufgabe war die Entwicklung eines hocheffizienten, hochtemperaturtauglichen und zeitstabilen Thermogenerators (TEG) für den Einsatz im Abgasstrang von Kraftfahrzeugen. Herkömmliche Lösungen sind aufgrund der geringen Hochtemperaturstabilität der Materialen nicht brauchbar und neuartige Materialien und Verbindungsstrukturen wurden entwickelt. Deshalb wurden thermoelektrische Modelle und Simulationen eingeführt, die eine frühe Vorhersage des Wirkungsgrades und der Energieersparnis durch das TEG-System ermöglichen.
Dafür wurden Silizium-Thermoschenkel durch Silizidierung auf einem thermisch leitenden Isolator legiert. Die entstandenen TEGs waren vom Wirkungsgrad nicht optimal, wiesen aber eine hohe thermische Stabilität auf. Gegenüber Lotverbindungen wurde eine deutliche Verbesserung des Degradationsverhaltens bei Hochtemperaturen sowie bei Temperaturwechselvorgängen erreicht. Die Effizienz der Generatoren wurde durch Ersatz der Si-Thermopaare mit alternativen Legierungen gesteigert.
Für die Simulation der TEGs wurden ANSYS und CST benutzt. Für beide Softwares wurden Methoden zur Modellerstellung entwickelt, die Parameterstudien in vertretbarer Zeit erlaubten. Verschiedene Materialien und Aufbauten wurden somit simuliert und bewertet. Der Vergleich mit realen Messungen zeigte eine gute Übereinstimmung. Parameterstudien in Bezug auf die Schenkelhöhe zeigten, dass mit Hilfe der Simulation eine schnelle Optimierung geometrischer Parameter möglich ist.


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SMART MONITORING

Smart Monitoring addresses the development of system solutions for condition monitoring or environmental monitoring using MEMS/NEMS-based systems including optimized data analysis and communication. Moreover, the focus is on monitoring systems for logistics which are based on printed antennas or printed batteries. Fraunhofer ENAS is working on:

- Structural health monitoring of lightweight structures, including reliability assessments
- Monitoring in logistics (transport monitoring, stock monitoring,…)
- Silicon-based micro-opto-electromechanical systems MOEMS in miniaturized spectrometers for gas analysis, environmental monitoring and medical applications
- Power line monitoring for utilizing the capacity of power lines
- Condition monitoring in mechanical engineering

In the last annual report we presented special developments in the field of mechanical engineering, namely results of the cluster of excellence MERGE as well as a grease monitoring system commonly developed with Schaeffler AG. In general, a trend toward implementing sensors, electronics for signal conditioning, wireless signal transmission (necessary due to rotating parts) and self-sustaining power supply to minimize machine failures can be observed.

So, the integration of microelectronic components and sensors into hybrid structures leads to the improvement of the performance and functional density of hybrid components themselves. The first article describes an innovative concept of detection, visualization and storage of mechanical loads on structural elements based on quantum dots.

The second article addresses wireless identification of products in logistics with the goal of optimizing the warehouse and transport logistics to save costs. Therefore, so-called Radio Frequency Identification (RFID) transponders are attached to products or their package.

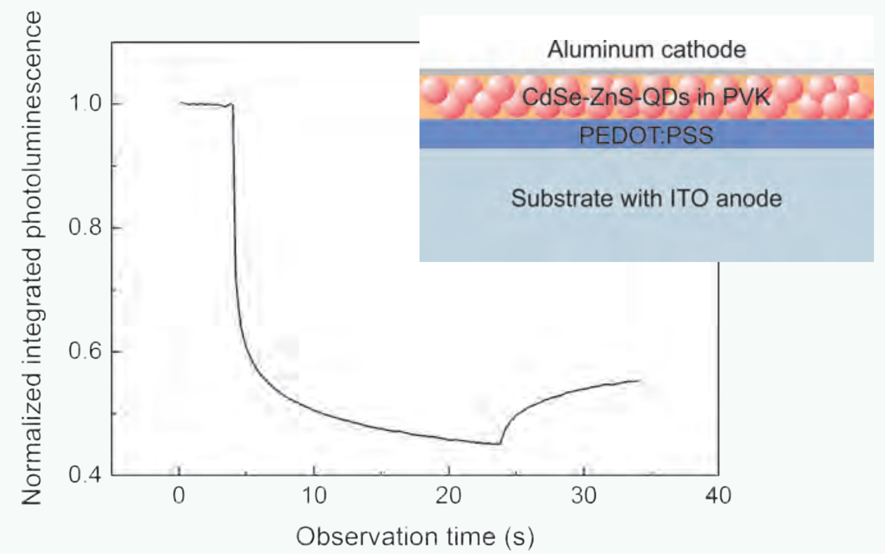
Smart Monitoring adressiert die Entwicklung von Systemlösungen für das Zustands- oder Umweltmonitoring basierend auf Mikrosystemen sowie optimierter Datenanalyse und Kommunikation. Darüber hinaus stehen Monitoringsysteme für die Logistik, welche gedruckte Antennen oder Batterien enthalten, im Fokus. Fraunhofer ENAS arbeitet in den Schwerpunkten:

- Monitoring von Strukturleichtbauteilen einschließlich Zuverlässigkeitsbewertung
- Monitoring in der Logistik (Transportmonitoring, Monitoring im Lager, ...)
- Siliziumbasierte Aktoren in miniaturisierten Spektrometern für Gasanalyse, Umweltmonitoring und Medizintechnik
- Freileitungsmonitoring zur Gewährleistung der Auslastung des Netzes
- Zustandsmonitoring im Maschinenbau

Die beiden nachfolgenden Artikel stellen unterschiedliche Themen vor. Der erste Artikel stellt Monitoring im Strukturleichtbau in den Mittelpunkt der Betrachtungen und beschreibt ein neues Konzept der Detektion, Visualisierung und Speicherung mechanischer Belastungen in Strukturleichtbauteilen mittels Quantumdots. Diese Untersuchungen sind im Kompetenznetzwerk nanett erfolgt.

Der zweite Artikel adressiert die drahtlose Identifikation von Produkten in der Logistik mit dem Ziel, Lagerhaltung und Transport zu optimieren, um Kosten zu sparen. Dafür werden RFID Transponder am Produkt oder der Verpackung platziert.

1



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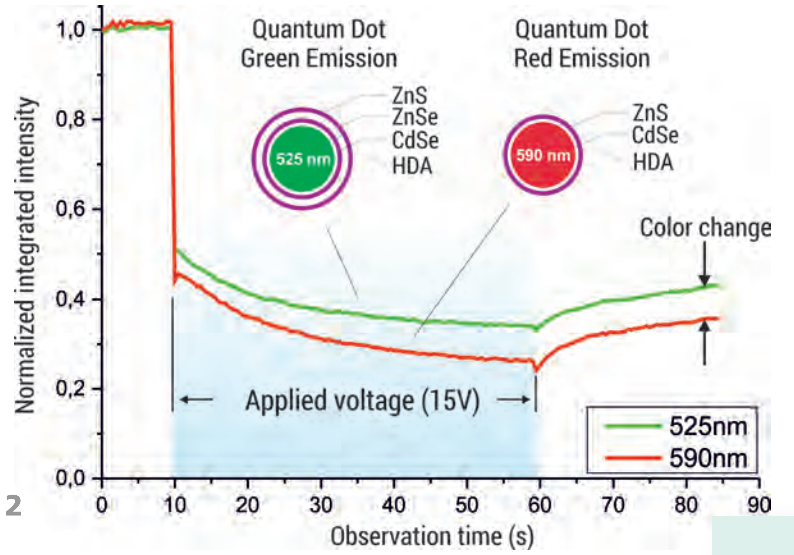

QUANTUM DOTS AS NANO SENSORS FOR VISUALIZATION OF MECHANICAL LOADS

Kathleen Heinrich, Martin Möbius, Jörg Martin

Semiconductor nanocrystals (quantum dots, QDs) form a unique material class with outstanding properties. During the past decades a lot of interesting photo physical effects of QDs have been revealed. Meanwhile quantum dots are not only of interest for basic research, but also for applications, such as QD-LEDs [1] or displays [2]. However, due to their sensitivity to electrical fields and charges, semiconductor nanocrystals are excellent nano sensors as well.

Recently we have presented a novel concept of detection, visualization and storage of mechanical loads on structural elements based on quantum dots [3]. In cooperation with partners of TU Chemnitz, Fraunhofer IAP and Leibniz IPF, first sensor patterns have been manufactured and tested within the framework of the 'Nano System Integration Network of Excellence – nanett'. Key feature of the sensor setup is a combination of a piezoelectric foil and a quantum dot composite layer, which are attached to or integrated into the mechanical component, e.g. lightweight structure. In case of mechanical impacts, dynamic loads or pressures, electrical charges are generated and injected into the QDs. Because of the fact that an additional delocalized charge within a nanocrystal leads to PL quenching, mechanical loads are transformed to a locally reduced PL, visible as optical contrast.

Figure 1 shows a typical integrated photoluminescence signal of a quantum dot composite sample (see insert of figure 1 for sample structure). At an observation time of 4 seconds an external voltage of 5 volts is applied, leading to a considerable reduction of PL intensity to 45 percent of initial value via charge injection mechanism. The achievable optical contrast depends on several factors, such as applied voltage, layer thickness and charge mobility/current. Removal of the external voltage (at 24 seconds) is followed by a slow increase of PL up to the initial value. Charges - and thus the optical contrast - are stored a certain time within the QDs depending on barriers around the QDs (shells) and the electronic band level alignment between QDs and matrix material. The relative short recovery time is very suitable for investigation of photo physical processes as well as demonstration purposes, and can be extended by alternative material combinations of QDs and matrix material.

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Within a project of the cluster of excellence 'Merge Technologies for Multifunctional Lightweight Structures – MERGE', the described basic concept of visualization of mechanical loads via bright-dark-contrast is extended towards photoluminescence color changes. This is realized by usage of a mixture of different types of quantum dots, e.g. core-shell and core-double-shell, within a single composite layer. In Fig. 2 the resulting photoluminescence of QDs biased with an external voltage of 15 V is depicted. The composite layer consists of a mixture of CdSe-ZnS QDs (orange emission) and CdSe-ZnSe-ZnS QDs (green emission). Records of spectral PL series and integration of respective emission bands demonstrate differences in quenching behavior and recovery. 'Orange particles' show stronger quenching and a slightly faster recovery, which is a consequence of obviously higher charge tunneling probability of this type of QDs.

A major challenge is the integration of sensor layers into lightweight structures, e.g. by lamination of respective foils. Besides ensuring the visibility of the optical contrast and reduction of charge consumption, also the stability of the sensor function is of great importance. In current work the sensor layers are optimized regarding the mentioned parameters.

Aufgrund ihrer Empfindlichkeit gegenüber elektrischen Feldern und Ladungen können Halbleiter-Nanokristalle (Quanten-Punkte, QP) nicht nur als reine Lichtemitter, sondern auch als exzellente Nanosensoren Verwendung finden. Auf der Basis von Quanten-Punkten konnte vom Fraunhofer ENAS ein neues Konzept zur Visualisierung von mechanischen (Über-) Lasten vorgestellt werden. Herzstück ist die Kombination einer piezoelektrischen Folie mit einer QP-Komposit-Schicht, womit die mechanische Last in eine lokal reduzierte Photolumineszenz (PL) der Partikel umgewandelt wird, was letztendlich als optischer Kontrast sichtbar ist. So konnte an Testmustern beispielsweise mit einer angelegten Spannung von 5 V eine Reduzierung der PL um mehr als 50 % erreicht werden. Zudem war es möglich, mit einer Mischung von unterschiedlichen Nanopartikeln ein farbspezifisches Schalten und damit einen gewissen Farbumschlag zu realisieren. Eine große Herausforderung ist die Integration der Sensorschichten in Leichtbaustrukturen. In aktuellen Arbeiten werden diesbezüglich unter anderem die Sichtbarkeit des optischen Kontrasts oder auch die Stabilität der Sensorfunktion untersucht.

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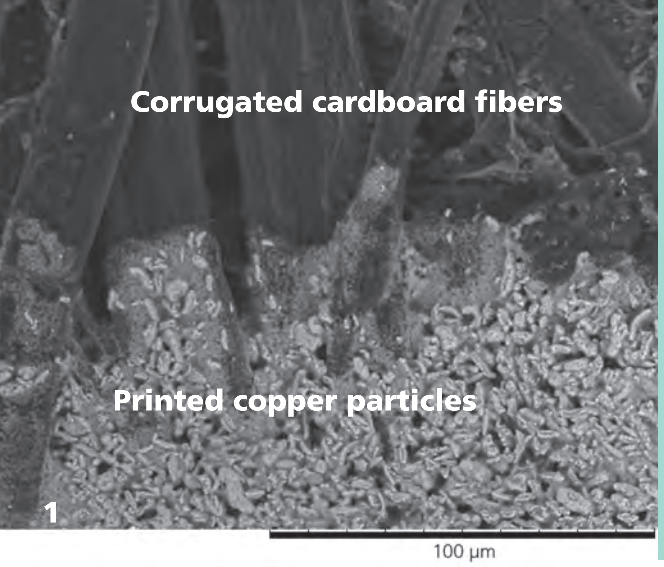
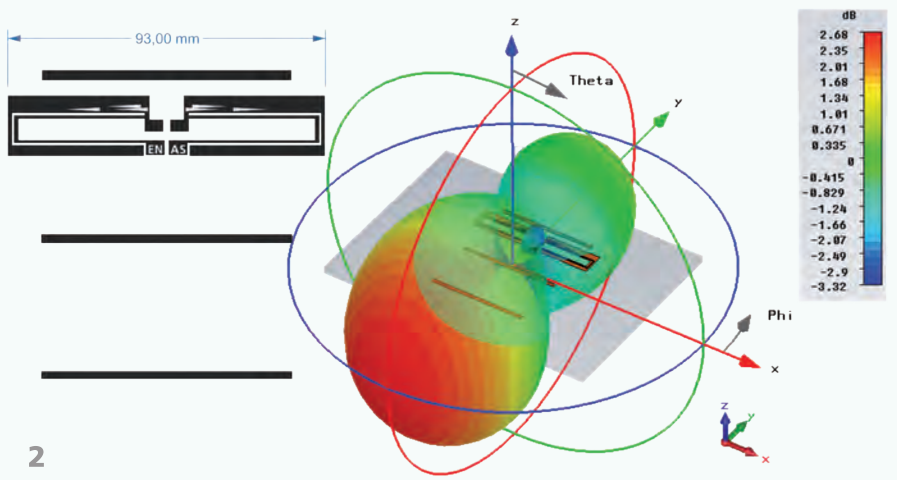
1 *Integrated photoluminescence of CdSe-ZnS quantum dots biased with an external voltage of 5 V between 4 and 24 s observation time. Insert shows sample structure.*

2 *Integrated photoluminescence of QD sample with CdSe-ZnS core-shell particles (emission @ 590 nm) and CdSe-ZnSe-ZnS core-double-shell particles (emission @ 525 nm). Between 10 and 60 s of observation time an external voltage of 15 V is applied.*





3

PRINTED ANTENNAS ON CARDBOARD BOXES ENABLING IDENTIFICATION OF METAL OBJECTS IN SUPPLY CHAINS

Ralf Zichner, Reinhard R. Baumann

The reliable wireless identification of products in supply chains is a key technique in logistics. The aim of the reported project was to optimize the warehouse and transport logistics to save costs. In order of wireless identification Radio Frequency Identification (RFID) transponders are attached to the items to be traced. These transponders consist of a Si-chip which is connected to an appropriate antenna. In the memory of the Si-chip the product data are stored. The transponder antenna assures the wireless communication between the transponder and an external RFID reader. In the ultra high frequency (UHF) range the energy and data transfer between RFID reader and transponder is based on electromagnetic waves in the frequency range of 868 MHz to 928 MHz. Standardized (dipole)-RFID transponders in industry are in general produced on a plastic substrate via printed circuit board (PCB) manufacturing processes. Their performance is strongly influenced by close metallic objects which is caused by the interaction of the dipole-typical omnidirectional radiation characteristic and the high electromagnetic reflectivity of metals.

Thus, in order to increase the profitability resp. the reliability of RFID transponders the projects motivations are:

a) reduction of manufacturing costs
b) increase of communication capability and reliability near metal objects

Reduction of manufacturing costs of RFID transponders

A reduction of the manufacturing costs can be achieved by employing printing technologies for the production of the transponder antennas. This is due to the remarkably reduced process time of printing technologies compared to wet-processing PCB techniques and the additive nature of printing: cost-intensive materials are deposited in locations only where the material is required. In detail, the following investigations were carried out to reduce the manufacturing time and to safe material:

- Application of the printing technology screen printing for manufacturing the transponder antennas directly on corrugated cardboard packages in one process step taking into account the high surface roughness of the corrugated cardboard of 9.9 µm ± 0.7 µm (see figure 1)
- Investigation of the printability of new low-cost copper inks
- Study of the Intense Pulsed Light (IPL) technology, time-reduced wave-based post treatment method for the functionalization/sintering of the printed copper ink patterns (antennas)

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It turned out that screen printing of the copper paste CP-002 (Intrinsiq Materials Inc. http://intrinsiqmaterials.com) and a subsequent flash treatment of the ink pattern was successful. In one process cycle (screen printing and a 1.2 ms IPL pulse) closed copper layers could be generated (see figure 1). The resulting sheet resistance of the printed copper layer is 40 mΩ/□ which is suitable to manufacture well functional antennas.

Increase of communication capability / communication reliability

The communication capability of antennas near metallic objects was improved based on a customized antenna design (see figure 2). The antenna design is a planar structure and consists of 4 elements (a reflector, a dipole and two directors). All elements interact with each other and thus cause the directional antenna radiation characteristic shown in figure 2. The influences of the metallic object on the propagation of the electromagnetic wave of the transponder antenna could be radical reduced by optimizing the geometry of the arrangement of the interacting objects.

Proof of communication capability / communication reliability

The proof of the communication capability and quality of the developed RFID antenna design was produced under industrial conditions provided by our project partner “richter & heß Verpackungsservice GmbH, Chemnitz”. For this purpose the RFID transponder antennas were printed on corrugated cardboard boxes (see figure 3) and commercially available RFID chips (NXP UCODE G2XM) were connected. The corrugated cardboard boxes were filled with metal containers (containing a fluid) and stacked on a pallet. In a series of experiments this assembly of RFID-tagged packages on a transport pallet was passed through a regular RFID reader gate and 100 percent of the printed RFID transponders could be identified.

Acknowledgment

The research activities described here were funded by the Sächsische Aufbaubank (SAB project number 100105339, EFRE-Europäischer Fonds für regionale Entwicklung).

Im durch die Sächsische Aufbaubank (SAB project number 100105339, EFRE-Europäischer Fonds für regionale Entwicklung) geförderten Forschungsvorhaben wurde durch das Fraunhofer ENAS die drucktechnische Herstellung von RFID-Transponder-Antennen direkt auf die Innenseite von Wellpappverpackungen untersucht. Das Antennenlayout wurde wahlweise mittels Siebdruck und Inkjetdruck unter Verwendung geeigneter Kupfer-Druckpasten auf die Verpackung appliziert. Die Ziele der Untersuchungen waren (1) Reduzierung der Herstellungskosten und (2) deutliche Verbesserung der Kommunikationsqualität/Kommunikationszuverlässigkeit von RFID-Transpondern in der Nähe von metallischen Objekten.
Beide Ziele konnten in einer industriellen Logistik-Umgebung bei unserem Projektpartner „richter & hess Verpackungsservice GmbH, Chemnitz“ erreicht werden. Die hergestellten RFID-Transponder-Antennen erlauben in Kombination mit einem handelsüblichen UHF-RFID-Chip die sichere, drahtlose Identifikation von Wellpappverpackungen, die flüssigkeitsgefüllte metallische Objekte enthielten.

1 *SEM image of printed copper particles on a corrugated cardboard.*

2 *Customized antenna design and its radiation characteristic based on a simulation.*

3 *Screen printed RFID antenna on a corrugated cardboard box.*

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SMART SENSING

High-precision micro-electromechanical systems and nanoelectromechanical systems are some of the unique features that distinguish Fraunhofer ENAS within the Fraunhofer-Gesellschaft. In order to strengthen this competence, Fraunhofer ENAS is working on different technologies, nano-based sensors as well as low-power MEMS, among them:

- Magnetic field sensors based on GMR spin valves
- Sensors based on carbon nanotubes
- Integration of strain-sensitive field effect transistors for NEMS
- Improvement of BDRIE technology for high-precision MEMS
- Piezoelectric low-power MEMS

The sensors presented in this chapter are not dedicated to a special application but can be used in different fields. So, the magnetic field sensor, which is a main component in a variety of mechatronic and electronic devices, can be applied in the automotive, in power electronics and navigation sectors as well.

Carbon nanotubes are not only an interesting material for transistors but also e.g. for sensors measuring the extension. As the function of CNT-based devices is often governed by quantum effects, their properties depend strongly on their dimensions and structural details. As CNTs used in applications are never defect-free, an understanding of the influence of the defects on the performance of CNT devices is required.

An alternative concept to the downscaling capacitive principles and to the piezoresistor gauge sensors is the application of transistors to transduce strain into an electrical signal. This is described in the third article.

The fourth article focuses on aluminum nitride which is a ground-breaking material for MEMS and NEMS sensors and actuators. Fraunhofer ENAS and the Center for Microtechnologies of TU Chemnitz use AlN for generating piezoelectric low-power MEMS.

Hochpräzise mikroelektromechanische und nanoelektromechanische Systeme gehören zu den Alleinstellungmerkmalen des Fraunhofer ENAS innerhalb der Fraunhofer-Gesellschaft. Um diese Kompetenz langfristig zu stärken, arbeitet Fraunhofer ENAS an verschiedenen Technologien, nanobasierten Sensoren sowie MEMS mit geringem Energiebedarf, u. a. an:

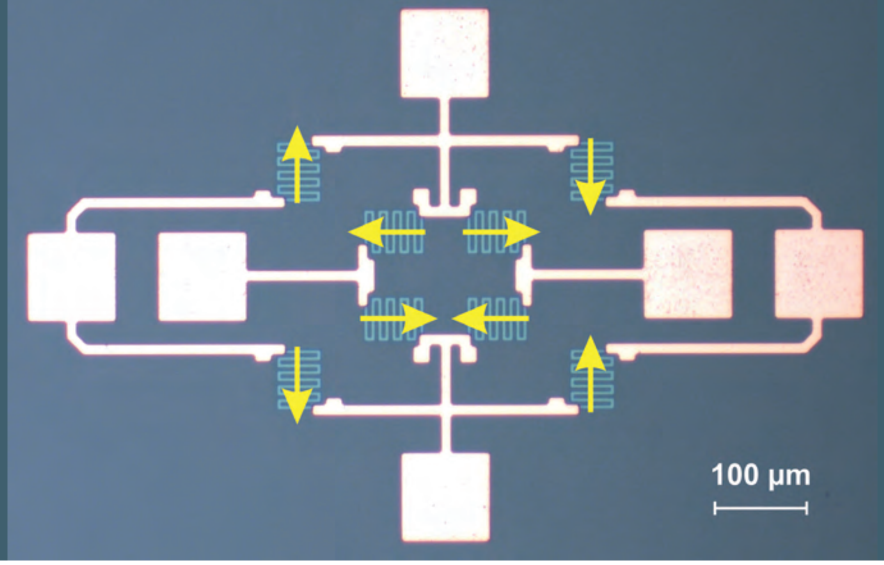
- Magnetfeldsensoren auf Basis von GMR-Spinventilen
- Sensoren auf Basis von Kohlenstoffnanoröhren
- Dehnungssensitiven Feldeffekttransistoren
- Verbesserung der BDRIE-Technologie für hochpräzise MEMS
- Piezoelektrische MEMS mit geringem Energiebedarf

Die in diesem Kapitel vorgestellten Sensoren sind nicht für eine spezielle Anwendung entwickelt worden, sondern können in verschiedenen Bereichen eingesetzt werden. So kann der Magnetfeldsensor als wesentlicher Bestandteil moderner Mechatronik- und Elektroniksysteme in der Automobilindustrie, der Leistungselektronik oder der Navigation angewendet werden.

Kohlenstoffnanoröhrchen sind nicht nur ein viel versprechendes Material für Transistoren, sondern sind beispielsweise auch als Dehnungssensoren verwendbar. Da die Funktion der CNT-basierten Bauelemente entscheidend von quantenmechanischen Effekten auf atomarer Skala bestimmt werden, sie aber real nie defektfrei sind, ist ein Verständnis des Einflusses von Defekten auf die Leistungsfähigkeit der Bauelemente wesentlich.

Der dritte Artikel beschreibt die Nutzung des piezoresistiven Effektes im Kanal eines Transistors als alternativen Ansatz für monolithisch integrierte Wandlerelemente.

Aluminiumnitrid als zukunftsweisendes Material für MEMS und NEMS, im speziellen Fall für piezoelektrische MEMS mit geringem Energiebedarf, steht im Mittelpunkt des vierten Artikels.



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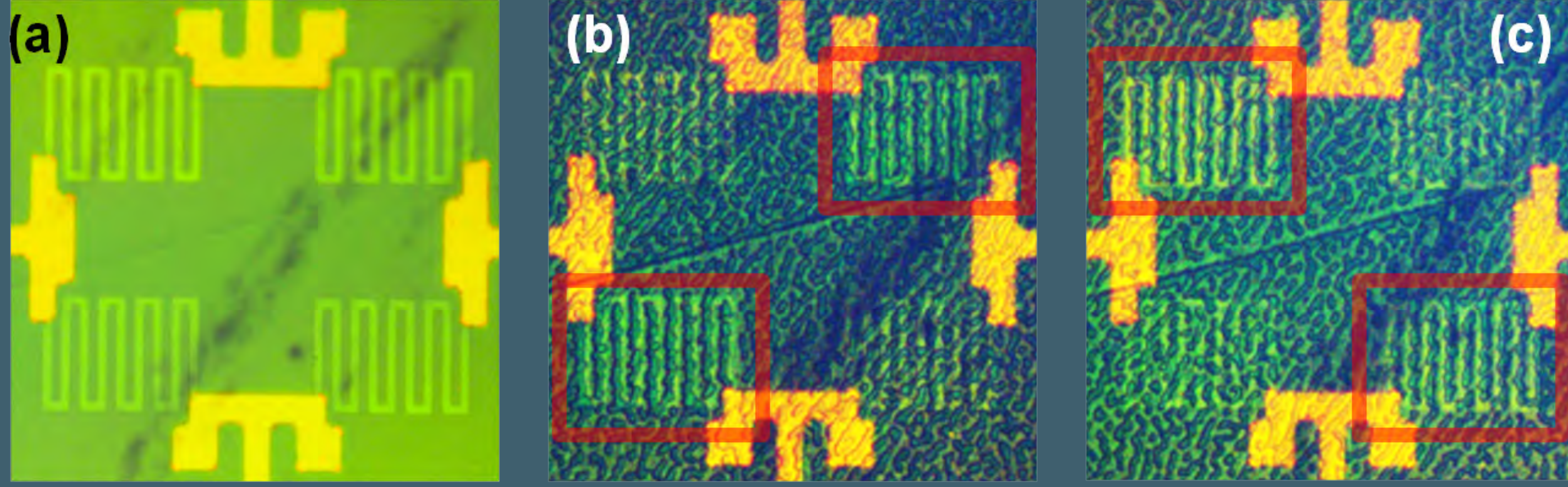

2

MONOLITHICALLY INTEGRATED 2D MAGNETIC FIELD SENSORS BASED ON GMR SPIN VALVES

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Magnetic field sensors have become omnipresent in everyday life. Being free of wear and small in size, they prove indispensable in a vast variety of mechatronic and electronic devices. For instance, they are used in large numbers in every modern car for providing precise information on the position of doors and steering units or on the rotation speed of wheels and shafts. They also serve as contactless gauges for electric currents. The sensors thereby often work under challenging operating conditions, such as elevated temperature or reactive atmospheres.

Magnetic field sensors are also prominent as built-in components of smartphones: Possessing multi-dimensional sensitivity there, they serve as electronic compasses for precise navigation by means of the geomagnetic field. For this specific application it becomes apparent that not only the measurement of the pure magnitude of a magnetic field, but also the detection of its direction is imperative. Classically, three independent Hall sensors were employed for such purposes. However, the ever-growing demands for further miniaturization, energy efficiency as well as accuracy and precision have paved the way for the superior magnetoresistive sensor technology. The giant magnetoresistance (GMR) effect (Nobel Prize for Physics in 2007) as applied in so-called spin valve sensors represents one of the market-leading technologies.

We have designed and manufactured 2D GMR spin valve sensors in an innovative and cost-effective monolithic integration. For this, the entire sensor device is fabricated from the very same piece of wafer by means of a specific laser-based post-processing step for magnetic patterning. As sensor materials, we use partially exchange-coupled metallic nanolayers and structure them in the form of centred double full Wheatstone bridges of meanders by plasma etching, see figure 1. For a maximum signal-to-noise ratio, an antiparallel alignment ("pinning") of the magnetic axes of neighbouring bridge meanders is accomplished. In addition, the axes of the two nested bridges must be rotated by 90° relative to each other for providing 2D sensitivity, cf. figure 1. Together with our partner Laserinstitut Hochschule Mittweida, we have successfully established this precise magnetic micro-patterning process by laser modification. The resulting magnetic structure can be visualized by magneto-optical microscopy, see figure 2.

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We further optimized the sensors characteristics in terms of maximum signal sensitivity and minimum hysteresis: By experiments and micromagnetic simulations we systematically studied how the geometry (stripe width, length, U-turns, total length, …) of the constituent single meanders influences the total magnetic structure and the electronic response. Moreover, we investigated the impact of pinning orientation and shape anisotropy on the sensor sensitivity.

Applying the best suited meander geometry obtained by our research, we eventually demonstrated that the developed 2D sensors can readily be employed for determining the magnitude and the direction of small magnetic fields with high spatial (~1 mm) and temporal (~1 ms) resolution.

Magnetfeldsensoren finden sich aufgrund ihrer hervorragenden Eigenschaften (Verschleißfreiheit, Temperaturbeständigkeit, geringe Größe etc.) als essenzieller Bestandteil moderner Mechatronik- und Elektroniksysteme in den unterschiedlichsten Anwendungsbereichen wieder, so z. B. in der Automobilindustrie, im Leistungselektroniksektor oder in der Navigation. Eine der aktuellen Kerntechnologien basiert dabei auf dem Riesenmagnetwiderstandseffekt (GMR, Nobelpreis 2007).
Wir haben einen leistungsfähigen 2D-GMR-Spinventil-Sensor mit dem Ziel der Kompassanwendung entwickelt. Insbesondere wurde hierbei in Kooperation mit dem Laserinstitut der Hochschule Mittweida die ebenso innovative wie ökonomisch vorteilhafte monolithische Integration erzielt, bei der die einzelnen Sensorkomponenten aus demselben Substrat gefertigt werden. Die von uns systematisch optimierte Doppelvollbrückenanordnung liefert ein signifikant gesteigertes Signal-zu-Rausch-Verhältnis bei gleichzeitig hoher Sensitivität und hinreichend kleiner Baugröße. Somit sind Betrag und Richtung von kleinen Magnetfeldern mit hoher räumlicher (~ 1mm) und zeitlicher (~1 ms) Auflösung messbar.

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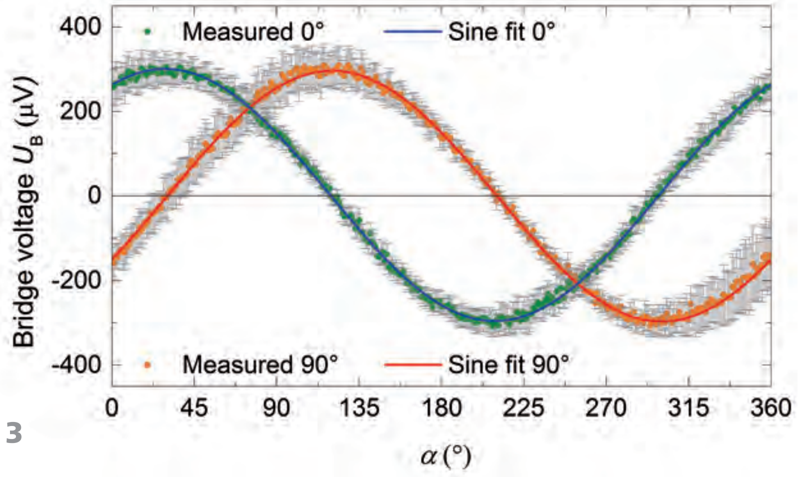
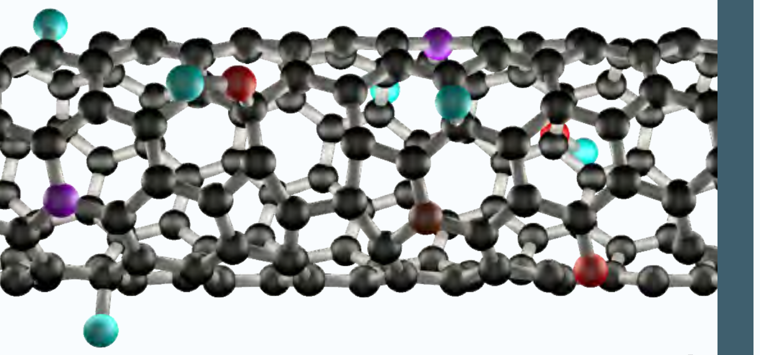


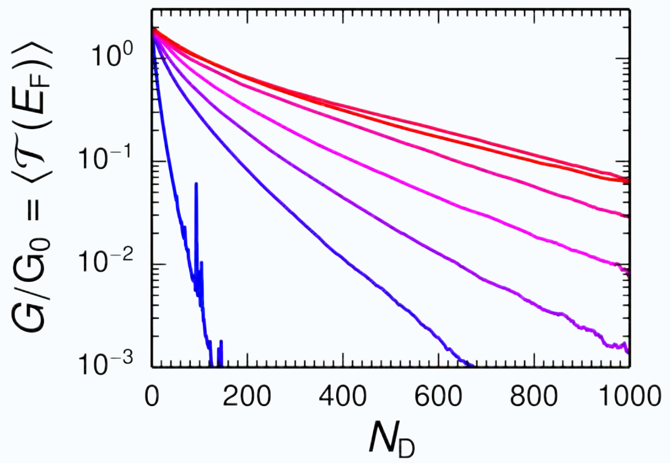
3

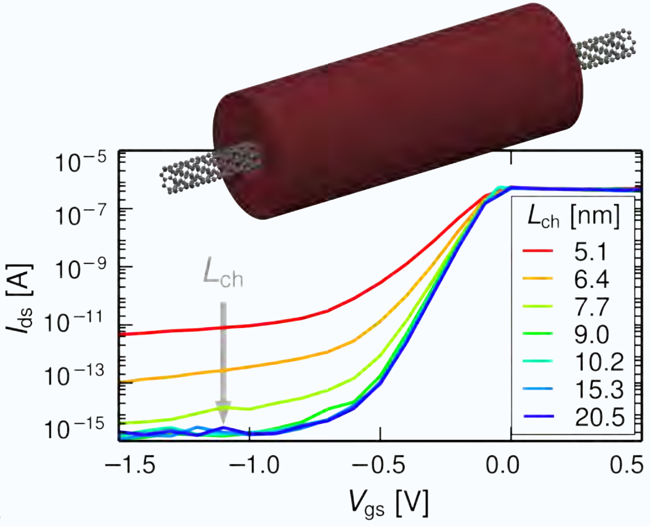
1 Microscopic image of a fully functional 2D sensor prototype. The sensor consists of two nested Wheatstone bridges, each constituent spin valve meander possessing an individual magnetic axis (yellow arrows) [1].

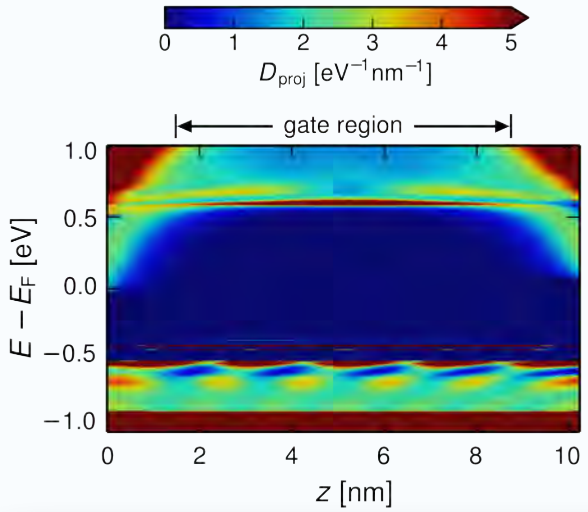
2 Laser-based magnetic patterning in magneto-optical visualization. By applying a suitable magnetic field, the laser-set magnetic axes become observable in terms of a slightly enhanced meander contrast: (b) bottom-left / top-right, (c) top-left / bottom-right, (a) initial state [1].

3 Sensor response to a 360° rotation in the ambient field of ~50 µT as measured at 1 kHz. The second curve (orange) was acquired after a sample rotation of 90° [1].









1 Schematic view of a carbon nanotube with defects.

2 Conductivity of defective carbon nanotubes with different diameters (increasing diameter from blue to red).

3 Transfer characteristics of the CNTFETs with decreasing channel length.

4 Visualization of the density of states within the transistor channel (channel length 10 nm, V_{gs} −0.8 V). The bending of the conduction band is clearly visible while the valence band is fixed due to the existence of localized states.

SIMULATION OF DEVICES BASED ON CARBON NANOTUBES

Jörg Schuster, Florian Fuchs, Fabian Teichert, Andreas Zienert, Stefan E. Schulz, Thomas Gessner

Carbon nanotubes (CNTs) are promising materials for future electronic devices due to their extraordinary mechanical strength in combination with excellent electronic and thermal properties. Technological concepts for the wafer-level integration of CNTs for sensor, transistor, and interconnect applications are currently developed at Fraunhofer ENAS and the Center for Microtechnologies Chemnitz (ZfM).

The functionality of CNT-based devices is often governed by quantum effects. Properties depend strongly on the dimensions and structural details at the atomistic level. Thus, along with the technology developments, adequate simulation concepts are required. Ab initio methods for the description of quantum effects have to be applied and linked to numerical device simulations, from which compact models for the circuit simulation can be derived. During the last years, methods for the simulation of nanodevices have been established at Fraunhofer ENAS in close cooperation with the more fundamental work groups at the ZfM. As an example, the contact properties of CNTs with various metals have been studied systematically [1].

A new tool for the efficient simulation of large quasi 1D structures: CNTs with structural defects

CNTs used in applications are never defect-free. Thus, a thorough understanding of the influence of defects on the performance of potential CNT-based devices is required.

In a recent study we have analyzed the influence of structural defects on the electronic transport in metallic CNTs [2]. The study focuses on CNTs with a length of up to several microns and a very high number of defects. This is a big challenge for quantum simulation methods like DFT, where the computational effort is proportional to the 3rd power of the system size (or worse). Based on the recursive Green's function approach, a linear scaling simulation tool was implemented at Fraunhofer ENAS, which allows us to study systems of realistic size with quantum mechanical accuracy [2]. The approach is very general and can be applied to various kinds of quasi one-dimensional structures like CNTs, nanowires or polymers.

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Our work shows that the electron transport in CNTs with a high number of randomly arranged defects is in the regime of strong localization, where the conductance decreases exponentially with the number of defects. This is characterized by an exponential prefactor, which depends on the defect type, CNT diameter and temperature.

Device simulation of CNTFETs-based on quantum transport simulations

A simplified device model has been used to study doped CNTFETs with a channel length in the order of 10 nm (close to prototypes @ IBM) surrounded by a cylindrical gate. The software Atomistix ToolKit is used for the quantum transport simulations. The underlying electronic structure calculations are based on a semiempirical extended Hückel model with parameters that describe the transport in CNTs with DFT-like accuracy [3].

Transfer characteristics of CNTFETs with different channel- and gate lengths are obtained from a series of device simulations. All the simulated transistor configurations show very good switching behavior and very high on/off-ratios. A remarkable finding is the fairly good transistor performance even for extremely short gates of 0.4 nm. The best devices reached on/off-ratios of 10^7. By analyzing the spatially resolved density of states, we see that the band edges of the valence bands are fixed due to the presence of localized states within the gate region. This suppresses band-to-band tunneling and enables the excellent device performance.

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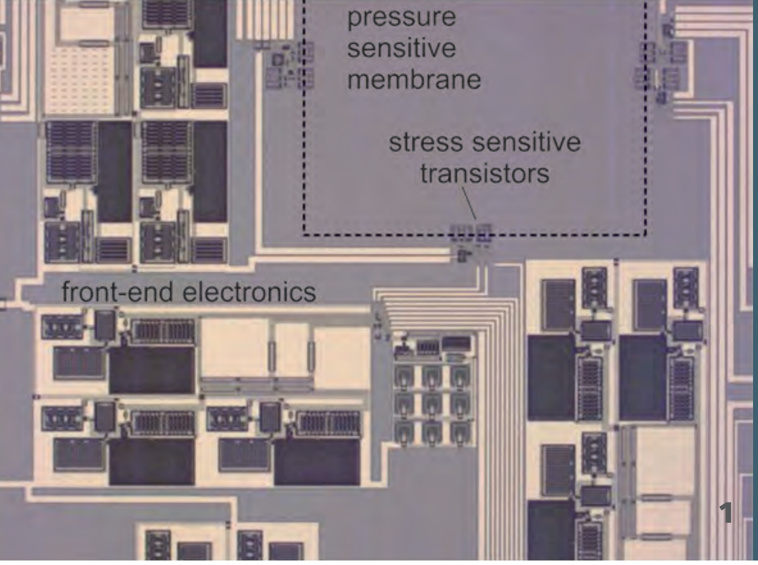
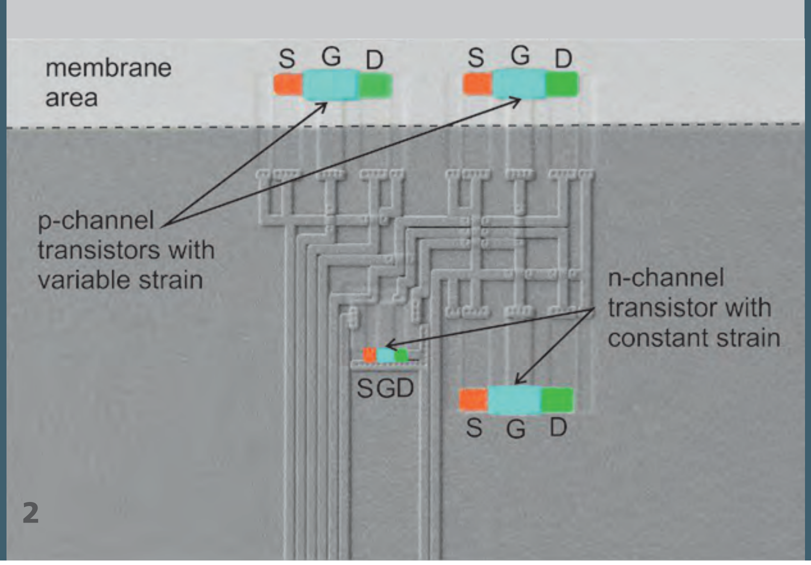
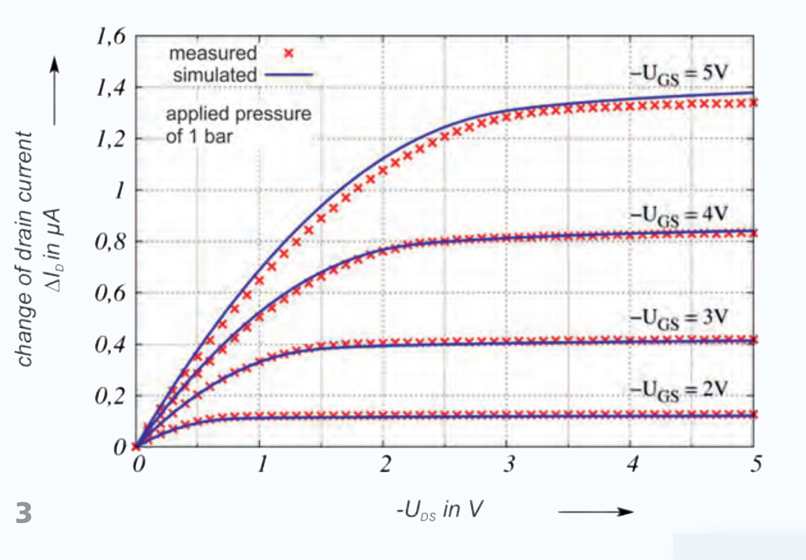
Kohlenstoffnanoröhren (CNTs) sind aufgrund herausragender Eigenschaften eine vielversprechende Materialklasse für zukünftige elektronische Bauelemente. Insbesondere für Sensoranwendungen und Hochfrequenzfeldeffekttransistoren werden am Fraunhofer ENAS und am Zentrum für Mikrotechnologien (ZfM) derzeit technologische Konzepte zur Integration von CNTs auf Wafer-Ebene entwickelt. Da die Eigenschaften von CNTs entscheidend von quantenmechanischen Effekten auf der atomaren Skala bestimmt werden, sind entsprechende Simulationskonzepte, die in den letzten Jahren am Fraunhofer ENAS in enger Kooperation mit dem ZfM etabliert wurden, unerlässlich. Beispielhaft hierfür sind die Entwicklung eines effizienten Simulationswerkzeugs zur Beschreibung großer quasi-eindimensionaler Systeme, wie etwa CNTs mit strukturellen Defekten, sowie die numerische Bauelementesimulation von CNT-Feldeffekttransistoren in Kombination mit einer quantenmechanischen Beschreibung des Elektronentransports.







1 Top view of the pressure sensitive membrane and the front-end electronics.

2 SEM picture of the stress sensitive transistors in a half bridge circuit.

3 Output characteristics of a p-channel transducer, the current change for 1 bar pressure difference is shown for different gate-source voltages.

DIRECT INTEGRATION OF STRAIN SENSITIVE FIELD EFFECT TRANSISTORS FOR NEMS

Sven Haas, Danny Reuter

Introduction

The drive to more compact and complex integrated NEMS is in need of further shrinking of the transducer elements at the same sensitivity as common used ones. Sensors based on the capacitive principle are scaling with the electrode area and piezoresistor gauge sensors need a certain length of the resistor to get a reasonable sensitivity. An alternative approach is the use of transistors to transduce strain in the channel into an electrical signal.

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MOS-Detection for nano size

Mechanical stress in the channel of a field effect transistor (FET) influences directly the charge carrier mobility and therefore the drain current and most of the transistor's other properties. This allows to shrink the transducer size between few micrometers and some hundred nanometers. The manufacturing with a common CMOS process additionally brings benefits to cost, size, sensitivity, signal-to-chip-area-ratio and power consumption. For principle studies on this effect, pressure sensitive membranes with strain sensitive transistors at their edges have been designed and fabricated in a 1.0 µm CMOS technology foundry run.

The strain sensitive FETs are connected in half-bridge mode consisting of two n-channel FETs and two p-channel FETs. It was designed to minimize impact of parasitic effects and temperature on the sensors as well as transferring the source drain current into a voltage, which can be very easily analyzed. In this bridge the p-channel FETs are used as the transducing elements. The source and bulk of the same types of transistors are connected to the input voltage. The drain contacts are connected to create a voltage from the stress influenced source-drain-current. The gate voltages can be controlled separately to adjust bridge voltage directly.

The evaluation circuit is integrated for on-chip amplification, gain adjustment and temperature compensation. This highly integrated system gives the advantage for a temperature measurement on the same chip in close proximity to the active transducer elements. This achieves measuring nearly the sensor temperature which leads to better compensation. Furthermore, the on-chip signal processing minimizes the influences of interconnects.

For design, layout and understanding of the transistor behavior the piezoresistive effect has been integrated into the circuit simulator ELDO from Mentor Graphics®. Therefore, the piezocoefficients of silicon and the stress sensitivity of the charge carrier mobility was added into the model to determine the relation between the mechanical stress and the transistor properties. The complete circuit including the stress sensitive transistors, the amplifiers and the signal processing was simulated to achieve the best performance for the used transducers. For optimizing the position of the transistors in relation to the stress maximum of the membrane, a simulation of the mechanical system has been made using a finite element model.

Für die zukünftig geplante Anwendung von Sensoren in allen technischen Systemen ist für die Erzielung der notwenigen Preise eine weitere drastische Reduzierung der Chipfläche von siliziumbasierten Mikrosystemen notwendig. Während konventionelle Wandlerprinzipien, wie piezoresistive Widerstände oder die Messung über kapazitive Sensoren, in ihrer Skalierbarkeit beschränkt sind, bietet die Nutzung des piezoresistiven Effektes im Kanal eines Transistors eine sehr gute Skalierbarkeit.

Für die Herstellung geeigneter Testchips wurden Transistormodelle modifiziert und das Verhalten der Feldeffekttransistoren in einer Schaltungssimulation analysiert. Die monolithisch integrierten Wandlerelemente wurden charakterisiert und lieferten bei deutlich reduzierter Chipfläche vergleichbare Empfindlichkeiten zu konventionellen Wandlern und einen deutlich niedrigeren Temperatureinfluss.

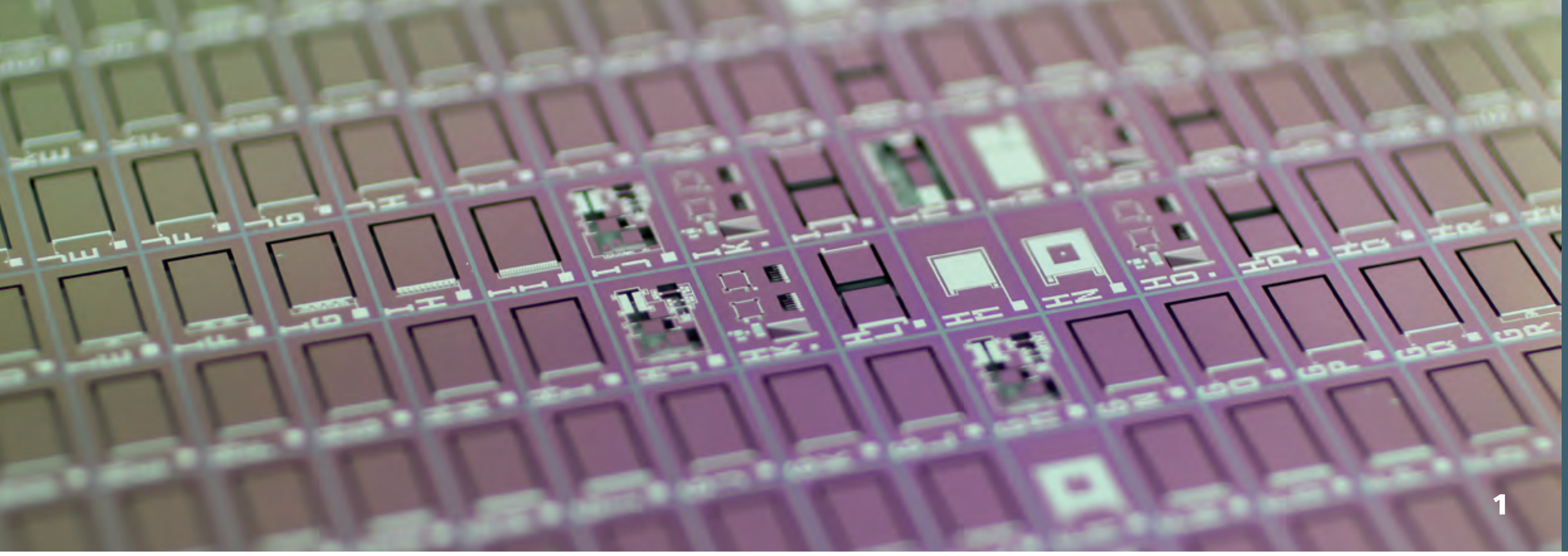
Measurement results

The measurements of a single transistor showed an increase in carrier mobility and therefore in drain current from an applied strain in good agreement with the simulation results (Fig. 3). An unamplified gauge factor of 110 could be determined for p-channel FETs, independently of the drain-source and gate-source voltage. The charge carrier mobility was extracted from the transfer characteristic at a drain-source voltage of – 50 mV. Without a stress influence the mobility lies between 190 and 193 cm²/Vs. The current of the reverse biased drain-bulk diode does not show stress influence, but in the breakdown region a gauge factor of 50 is calculated from the simulation.

The Wheatstone bridge configuration shows a linear dependence of pressure changes with 0.64 %-FSO. The test vehicles achieved a sensitivity between 83 and 91 mV/bar with a temperature coefficient of -126 ppm/K. This is a similar sensitivity in comparison to conventional measurement principles with good linearity and low temperature dependence without signal processing. The measured temperature dependence is by factor 16 lower than a conventional piezoresistor strain gauge.

Acknowledgment

This work was funded by the German Research Foundation within the Research Unit 1713.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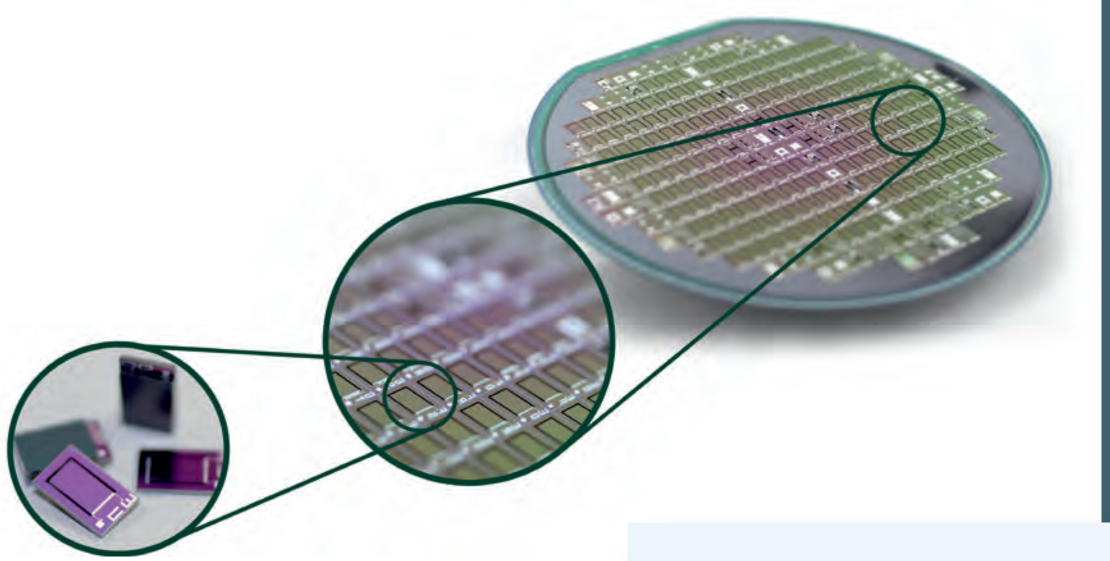
2

PIEZOELECTRIC LOW-POWER MEMS WITH ALUMINUM NITRIDE

Chris Stöckel, Detlef Billep, Thomas Otto

Aluminum nitride (AlN) is a seminal material for MEMS and NEMS sensors and actuators. The energy density of piezoelectric active principles is much higher than capacitive ones. This allows the shrinking of MEMS and NEMS, reduces costs and energy consumption and increases the areas of application. Thereby, piezoelectric driven MEMS (piezoMEMS) can replace capacitive applications.

AlN is highly capable of being integrated into micromechanical and CMOS processes. This is a significant benefit for AlN-based piezoMEMS system integration into CMOS-based integrated circuits, compared to Lead-Zirconate-Titanate (PZT) or polymer piezoelectric materials (PVDF). Furthermore, AlN has low aging effects and high temperature stability.

In cooperation with the Center for Microtechnologies a sputtering technology and characterization methods for piezoelectric thin film AlN are developed. Furthermore, a technology for an integration of the thin film into silicon MEMS is available, which allows a multi project wafer (MPW) production for flexible and customized prototype production.

Low-power applications

Exemplary, the development of ultra-low-power piezoMEMS, the Power-Down-Interrupt-Generator, is shown. The Power-Down-Interrupt-Generator (PDIG) is a MEMS device with a spring-mass-system and coupled AlN layer. In result of acceleration the PDIG deforms and the AlN generates electric charges. These charges will be used to wake up an electric circuit, e.g. a highly precise acceleration sensor. State of the art acceleration sensor measure constant and consume permanently electrical energy. With the use of the PDIG, the acceleration sensor is in the sleeping mode as long as a measurement is not required. If acceleration occurs, the PDIG wakes up the electrical circuit and therewith the acceleration sensor. As result the effective energy consumption shrinks to a minimum. Especially for wireless systems energy saving solutions are essential to minimize consumption, rise battery lifetime and save resources. Furthermore, the longer battery lifetime implies longer maintenance intervals. For measurement systems with difficult accessibility the energy saving has special economical advantages.

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Aluminiumnitrid (AlN) ist ein zukunftsweisendes Material für MEMS und NEMS. Die hohe Energiedichte, CMOS-Kompatibilität, geringe Alterungseffekte und hohe Temperaturstabilität machen AlN zu einem bevorzugten Material für MEMS-Applikationen.

Ein Sputterprozess für AlN Dünnschichten und die Technologie zur Integration des AlN in Silizium-basierte MEMS wurde entwickelt.

Der Power-Down-Interrupt-Generator (PDIG) ist eine Kleinstleistungsapplikation auf AlN-Basis. Bei einem mechanischen Ereignis generiert das MEMS eine elektrische Ladung intrinsisch und übermittelt das Signal an eine Elektronik. Da der PDIG keine Energiezufuhr benötigt, kann der Verbrauch des Gesamtsystems minimiert werden.

The industry-oriented piezoMEMS applications of the Fraunhofer ENAS base on fundamental research results in microtechnology and characterization. Wide knowledge of AlN growth processes exists. Detailed investigations of the dependencies to the piezoelectric behavior with the technology process are the fundament for high-end piezoMEMS. The permanent optimization of the sputtering conditions and advancement of the piezoelectric characterization tools for thin films are unique at the Fraunhofer ENAS and the Center for Microtechnologies. The Fraunhofer ENAS has unique methods for the precise determination of the piezoelectric coefficients d_{33} and d_{31} of thin films. A highly precise characterization of the AlN is the key for innovate piezoMEMS research and development.

With AlN the Fraunhofer ENAS has a CMOS compatible thin film material for the integration into silicon MEMS. In addition to permanently optimized AlN technology processes, the Fraunhofer ENAS has unique and highly precise characterization tools for the determination of the piezoelectric coefficients for thin films. Based on this fundament industry-oriented micro sensors and actuators are developed. The high coupling coefficient, CMOS compatible processes, intrinsic energy generation for ultra-low-power devices, out-of-plane actuation functions and many other advantages are the driving forces for the Center of Microtechnologies for the research and development of AlN-based cutting edge innovate piezoMEMS.

Acknowledgment

The work related to integration technologies of single and stacked components on PCB was partly supported by the European Union (EFRE) and by the Free State of Saxony, Germany, within the research project CoolPod funded by SAB-Foerderbank (100107775).

Europäische Union
Europa fördert Sachsen.
EFRE
Europäischer Fonds für regionale Entwicklung

1 *Integrated production of multiple MEMS devices on a multi project wafer.*

2 *Multi project wafer with sputtered piezoelectric AlN technology (right). Enlarged an array of PDIGs with a variation of electrode designs is shown (middle). Diced and partial packaged PDIGs (left).*

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ATTACHMENT

EVENTS

Chemnitz workshops on Nanotechnology, Nanomaterials and Nanoreliability

The Chemnitz workshop series on Nanotechnology, Nanomaterials and Nanoreliability have been successfully realized in 2014. The first one was the honorary workshop on occasion of Prof. Michel's 65th birthday on April 30th, 2014. Topic was reliability research for micro and nano technologies. Longtime cooperation partners and colleagues from industry and research presented latest advancements in the field of reliability analysis and prediction. The department System Packaging invited to the workshop "System Integration Technologies" on July 2nd, 2014. Fraunhofer researchers and guests discussed about current research and development results on wafer bonding and packaging technologies. The 20th workshop was held together with Electronic Design Chemnitz GmbH and the working group Smart Integrated Systems within the network Silicon Saxony e.V.. More than 100 experts attended the workshop "Smart Monitoring Systems" in Chemnitz.

International conferences and workshops

At the 8th Smart Smart Systems Integration Conference and Exhibition 284 attendees from 24 countries discussed about smart systems, manufacturing technologies, integration technologies and applications.
A similar big event has been organized on August 12th, 2014, on occasion of Professor Gessner's 60th birthday in Chemnitz. Nearly 320 participants listened to the presentations of national and international scientists and experts from industry to new developments in microelectronics, microsystems (MEMS and NEMS) as well as smart integrated systems.
Within the "Sendai Micro Nano International Forum 2014", the 10th Fraunhofer Symposium in Sendai was held on November 26th, 2014. The Fraunhofer Symposium especially focussed on smart systems for a secure world.

Chemnitzer Seminare

Die Chemnitzer Seminarreihe „Chemnitzer Seminare – Nanotechnology, Nanomaterials and Nanoreliability" wurde 2014 erfolgreich weitergeführt. Sie startete mit dem Ehrenseminar für Prof. Dr. Bernd Michel zum Thema „Zuverlässigkeitsforschung für Mikro- und Nano Technologien" am 30. April 2014, organisiert durch das Micro Materials Center. Wegbegleiter und Kooperationspartner aus Industrie und Wissenschaft würdigten nicht nur die Leistungen von Prof. Michel, sondern zeigten aktuelle Entwicklungen im Bereich Zuverlässigkeitsanalysen und -vorhersagen.
Fortgesetzt wurde die Reihe am 2. Juli durch die Abteilung System Packaging mit dem Thema „System Integration Technologies". Auf der Ganztagesveranstaltung stellten Fraunhofer-Wissenschaftler und Gäste aktuelle Forschungs- und Entwicklungsergebnisse zu Waferbondverfahren und Packaging-Technologien vor.
Das mittlerweile 20. Seminar wurde gemeinsam mit der Electronic Design Chemnitz GmbH und dem Arbeitskreis Smart Integrated Systems des Silicon Saxony e.V. organisiert. Zum Thema „Smart Monitoring Systems" trafen sich rund 100 Experten in Chemnitz.

Internationale Konferenzen und Workshops

Die achte Smart Systems Integration Konferenz 2014 fand in Wien, Österreich statt. 284 Teilnehmer aus 24 Ländern diskutieren über intelligente Systeme, Herstellungstechnologien, Integration und Anwendungen.
Eine vergleichbar große Veranstaltung war das internationale Symposium zum Thema Smart Integrated Systems zu Ehren des 60. Geburtstags von Professor Geßner mit insgesamt 320 Teilnehmern am 12. August 2014 in Chemnitz. Nationale und internationale Wissenschaftler und Experten aus der Industrie stellten aktuelle Entwicklungen auf den Gebieten Mikroelektronik, Mikrosystemtechnik und intelligente Systeme vor.
Bereits zum zehnten Mal wurde unter Chemnitzer Federführung das Fraunhofer-Symposium in Sendai am 26. November 2014 organisiert. Das im Rahmen des Sendai Micro Nano International Forum 2014 stattfindende Fraunhofer-Symposium stand unter dem Motto „Intelligente Systeme für eine sichere Welt".

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Science meets Arts

Fraunhofer ENAS presents an art exhibition series under the title "Science meets Arts" since 2009. In 2014, the 10th exhibition within this series was opened. Klaus Süß, a Chemnitz artist, shows color woodcuts, painted plates and sculptures. The title of his exhibition is "Ins Holz geschnitten" (english: "cutting into the wood").
In the first exhibiton in 2014, Vivien Nowotsch presented various works themed "Mut zur Farbe". She is studying arts at the Hochschule der Bildenden Künste in Dresden, Germany, and exhibited lithographies, charcoal drawings as well as oil and acryl paintings. In an interesting gallery talk she told about her life as an art student. We thank our curator, Georg Felsmann, for his very helpful support.

Chemnitz City Run – Chemnitzer Firmenlauf

A team of 23 employees of Fraunhofer ENAS and the Center for Microtechnologies of TU Chemnitz started at the 9th Chemnitz City Run on September 3rd, 2014. Our team consisted of six women and 17 men reaching the finish among 4653 runners. Our best male starter finished as 12th and our best female as 261st. Our best team of four men finished as 6th.

Public exhibition in Chemnitz

A public exhibition themed "Industrial City Chemnitz – Meeting Point Future" was opend in the shopping mall in downtown Chemnitz from September 8th to 23rd, 2014. Local companies and research instiutions presented their new products and research topics with attractive exhibits for the general public. Fraunhofer ENAS showed the ASTROSE® sensor node, a monitoring system for power lines. The institute also exhibited a part of an airplane wing with integrated jet actuators, microfluidic cartridges, an IR detector with a tunable filter, a MEMS spectrometer and an inclination sensor. One highlight was a table with integrated smart universal power antennas (SUPA), which transmitted power wireless to a monitor on the table top. The monitor showed promising technologies of the cluster cfaed which may complement today's leading CMOS technology for nanoelectronics.

Wissenschaft trifft Kunst

Seit 2009 veranstaltet das Fraunhofer ENAS die Ausstellungsreihe „Wissenschaft trifft Kunst". In diesem Jahr wurde die zehnte Ausstellung eröffnet. Klaus Süß, ein Chemnitzer Künstler, zeigte Farbholzschnitte und bemalte Druckstöcke sowie Skulpturen unter dem Titel „Ins Holz geschnitten". In der ersten Ausstellung des Jahres 2014 präsentierte Vivien Nowotsch, die derzeit an der Hochschule für Bildende Künste in Dresden studiert, einen umfangreichen Einblick in ihre Arbeiten. „Mut zur Farbe" bewies sie mit einer Auswahl an Lithografien, Kohlezeichnungen und Werken in Öl und Acryl. In einem interessanten Künstlergespräche berichtete sie außerdem aus ihrem Leben als Kunststudentin. Wir danken herzlich unserem Kurator Herrn Georg Felsmann für seine zahlreichen Ideen und die intensive Unterstützung bei der Organisation unserer Ausstellungsreihe.

Chemnitzer Firmenlauf

Zum 9. Chemnitzer Firmenlauf am 3. September 2014 startete eine 23-köpfiges Team des Fraunhofer ENAS und des Zentrums für Mikrotechnologien der TU Chemnitz. Die sechs Läuferinnen und 17 Läufer unseres Teams erreichten unter insgesamt 4653 Läufern das Ziel. In der Einzelwertung belegte unser bester Läufer insgesamt Platz 12 und unsere beste Läuferin Platz 261 aller gewerteten Frauen. Unser bestes Vierer-Team der Männer erreichte Platz 6.

Ausstellung in der Galerie Roter Turm, Chemnitz

Für Besucher des Einkaufszentrums „Galerie Roter Turm" in Chemnitz wurde vom 8. bis 23. September 2014 eine Ausstellung unter dem Motto „Industriestadt Chemnitz – Treffpunkt Zukunft" geboten. Unternehmen und Forschungseinrichtungen aus Chemnitz präsentierten in publikumswirksamen Exponaten ihre neuesten Produkte und Forschungsthemen. Das Fraunhofer ENAS stellte u.a. den ASTROSE®-Sensorknoten, ein Überwachungssystem für Hochspannungsleitungen, sowie einen Tisch, der kabellos Energie an einen Monitor liefert, aus.

CONFERENCES

Fraunhofer ENAS is organizer / co-organizer of the following conferences and workshops:

Materials for Advanced Metallization MAM 2014	Chemnitz, Germany	March 2 – 5, 2014
Smart Systems Integration Conference – co-organizer	Vienna, Austria	March 26 – 27, 2014
Conference "MicroClean 2014"	Lichtenwalde, Germany	May 14 – 15, 2014
Demoline LOPEC 2014	Munich, Germany	May 27 – 28, 2014
MEMUNITY Workshop – co-organizer	Grenoble, France	October 7 – 9, 2014
CMP Wet User Meeting	Grenoble, France	October 8 – 10, 2014
2nd European Expert Workshop on Reliability of Electronics and Smart Systems – 2014 EuWoRel	Berlin, Germany	October 28 – 29, 2014
ENDOR Workshop	Chemnitz, Germany	November 17, 2014
10th Fraunhofer Symposium	Sendai, Japan	November 26, 2014

In 2014 the scientists of Fraunhofer ENAS presented their results at 70 conferences and exhibitions accompanying conferences. Thereby 17 keynotes and invited presentations have been given. At all organized and co-organized conferences research results and project results have been presented. A selection of additional conferences is included in the following table.

iCT 2014 – 5th Conference on Industrial Computed Tomography	Wells, Austria	February 25 – 28, 2014
IWEPNM 2014 – International Winterschool on Electronic Properties of Novel Materials	Kirchberg in Tirol, Austria	March 8 – 15, 2014
DTIP Conference – Design, Test, Integration & Packaging of MEMS/ MOEMS	Cannes, France	April 1 – 4, 2014
EuroSimE 2014 – 15th international conference on thermal, mechanical and multi-physics simulation and experiments in microelectronics and microsystems	Ghent, Belgium	April 7 – 9, 2014
innoBATT Conference	Unterpremstätten, Austria	April 9 – 10, 2014
MEMS Engineering Forum	Tokyo, Japan	April 24 – 25, 2014
IITC/AMC 2014 – IEEE Internatioal Interrconnect Technology Conference / Advanced Metallization Conference	San Jose, USA	May 20 – 23, 2014
Applied Materials Customer Technology Symposium	Dresden, Germany	May 22, 2014
64th ECTC – IEEE Electronic Components and Technology Conference	Orlando / Florida, USA	May 27 – 30, 2014
ITHERM 2014 – IEEE Intersociety Conference on Thermal and Thermo-mechanical Phenomena in Electronic Systems	Orlando / Florida, USA	May 27 – 30, 2014
ALD Conference 2014	Kyoto, Japan	June 15 – 18, 2014

CONFERENCES

NEWCAS 2014 – 12th IEEE New Circuits and Systems Conference	Trois-Rivieres, Canada	June 22 – 25, 2014
AMAA 2014 – Advanced Microsystems for Automotive Applications	Berlin, Germany	June 23 – 24, 2014
QuantumHagen – Modeling of Electronic Devices and Materials at the Nanoscale	Copenhagen, Denmark	July 1 – 3, 2014
2nd International Conference on System-integrated Intelligence (SysInt)	Bremen, Germany	July 2 – 4, 2014
10th European Conference on Magnetic Sensors and Actuators	Vienna, Austria	July 6 – 7, 2014
NANOARCH 2014 – 10th ACM/IEEE International Symposium on Nanoscale Architectures	Paris, France	July 8 – 10, 2014
Dielectrophoresis 2014	London, UK	July 14 – 16, 2014
IEEE International Workshop on Low Temp. Bonding for 3D Integration	Tokio, Japan	July 15 – 16, 2014
MWSCAS 2014 – IEEE 57th International Midwest Symposium on Circuits and Systems	Texas, USA	August 3 – 6, 2014
UCPSS – 12th International Symposium on Ultra Clean Processing of Semiconductor Surfaces	Brussels, Belgium	September 21 – 24, 2014
EUROSENSORS 2014 – 28th European Conference on Solid-State Transducers	Brescia, Italy	September 7 – 10, 2014
IEEE RFID-TA 2014 – 5th IEEE International Conference on RFID Technology and Application	Tampere, Finland	September 8 – 9, 2014
MEMS Industry Group Conference Shanghai	Shanghai, China	September 11 – 12, 2014
ESTC 2014 – 5th Electronics System-Integration Technology Conference	Helsinki, Finland	September 16 – 18, 2014
IMEKO TC19 Symposium 2014 – 5th Symposium on Environmental Instrumentation and Measurements	Chemnitz, Germany	September 22 – 23, 2014
20th International Workshop on THERMAL INVESTIGATIONS OF IC´S AND SYSTEMS	Grenwich, London, UK	September 24 – 26, 2014
ESREF European Symposium on Reliability of Electron Devices, Failure Physics and Analysis	Berlin, Germany	September 29 – October 2, 2014
International Laser and Coating Symposium ILaCoS Asia	Shanghai, China	October 16, 2014
2nd International Conference on ALD Applications & 3rd China ALD conference	Shanghai, China	October 16 – 17, 2014
Advanced Metallization Conference 2014 – 24th Asian Session ADMETA Plus 2014 in Tokyo	Tokyo, Japan	October 22 – 24, 2014
12. Chemnitzer Fachtagung Mikrosystemtechnik	Chemnitz, Germany	October 21 – 22, 2014
IWLPC – International Wafer-Level Packaging Conference	San Jose, USA	November 11 – 13, 2014
MRS Fall Meeting – Material Research Society	Boston, USA	November 30 – December 5, 2014
Nano FIS – International Conference Functional Integrated nano Systems	Graz, Austria	December 3 – 5, 2014
ICECS 2014 – IEEE International Conference on Electronics Circuits and Systems	Marseille, France	December 7 – 10, 2014

EXHIBITIONS AND TRADE FAIRS

nano tech 2014	Tokyo / Japan	January 29 – 31, 2014
SEMICON China 2014	Shanghai, China	March 18 – 20, 2014
Smart Systems Integration 2014	Vienna, Austria	March 26 – 27, 2014
HANNOVER MESSE 2014	Hannover, Germany	April 7 – 11, 2014
China Chongqing Hi-Tech Fair 2014	Chongqing, China	April 10 – 13, 2014
nano micro biz 2014	Yokohama, Japan	April 23 – 25, 2014
SEMICON Russia	Moscow, Russia	May 14 – 15, 2014
Sächsische Industrie- und Technologiemesse 2014	Chemnitz, Germany	May 14 – 16, 2014
ILA Berlin Air Show 2014	Berlin, Germany	May 20 – 25, 2014
LOPEC 2014	Munich, Germany	May 27 – 28, 2014
SENSOR + TEST 2014	Nuremberg, Germany	June 3 – 5, 2014
Sensors Expo and Conference 2014	Rosemont, USA	June 25 – 26, 2014
Silicon Saxony Day 2014	Dresden, Germany	July 3, 2014
SEMICON Europa 2014	Grenoble, France	October 7 – 9, 2014
Chemnitzer MST-Fachtagung 2014	Chemnitz, Germany	October 21 – 22, 2014
COMPAMED 2014	Düsseldorf, Germany	November 12 – 14, 2014
NRW Nanokonferenz 2014	Dortmund, Germany	December 1 – 2, 2014
SEMICON Japan 2014	Tokyo, Japan	December 3 – 5, 2014

PATENTS

Fraunhofer ENAS holds 112 patents in 72 families. Moreover, employees of Fraunhofer ENAS belong to the inventors of additional 13 patent families hold by industry.
In 2014 the following patents have been published or granted:

Title: 3D Magnetfeldsensor und Verfahren zu dessen Herstellung
Number: DE 102014202770.5

Title: Mikromechanisches Bauteil zum elektrisch gesteuerten Verbinden und Unterbrechen eines Signalpfades
Number: EP 2395533 B1

Title: Prüfanordnung, Prüfsystem und Verfahren zum Prüfen eines Mikrosystems
Number: DE 10 2014 206 604.2

Title: Autonomous Active Flow Control System
Number: EP 14460033

Title: Vorrichtungen zur Aussendung oder zum Empfang elektromagnetischer Strahlung und Verfahren zur Bereitstellung derselben
Number: PCT/EP2014/072735

Title: Verfahren und Vorrichtungen zur Realisierung druckbarer Low-Cost-Spektrometer
Number: DE 10.2014 221 525.0

Title: Microelectromechanical System and Method for Manufacturing the Same
Number: PCT/EP2014/076609

Title: Microelectromechanical Switch and Method for Manufacturing the Same
Number: PCT/EP2014/076610

Title: Mikromechanisches Bauteil zum elektrisch gesteuerten Verbinden und Unterbrechen eines Signalpfades
Number: JP 673225

MEMBERSHIPS

Memberships of Fraunhofer ENAS Scientists

acatech (Council of Technical Sciences of the Union of German Academies of Sciences)	Prof. T. Gessner	member
Academy of Sciences of Saxony, Leipzig, Germany	Prof. T. Gessner	member
Academy of Sciences, New York, USA	Prof. B. Michel	member
Advanced Metallization Conference AMC, USA	Prof. S. E. Schulz	member of the executive committee
Arnold Sommerfeld Gesellschaft zu Leipzig	Prof. B. Michel	scientific advisory board
Board of “KOWI“, Service Partner for European R&D funding, Brussels, Belgium	Prof. T. Gessner	member
Conference on Wafer Bonding for Microsystems and Wafer Level Integration	Dr. M. Wiemer	committee member
Deutscher Verband für Schweißen und verwandte Verfahren e. V.	Dr. M. Wiemer	chairman AG A2.6 „Waferbonden“
Digital Fabrication Conference (DF) of IS&T	Prof. R. R. Baumann	fellow
Dresden Center for Computational Materials Science (DCCMS)	Prof. T. Gessner, Prof. S. E. Schulz, Dr. J. Schuster	members
Dresdner Fraunhofer Cluster Nanoanalytics	Prof. S. Rzepka	steering committee member
EGVIA (European Green Vehicle Association)	Prof. S. Rzepka	member
Engineering and Physical Science Research Council, UK	Prof. B. Michel	referee
EPoSS (European Platform on Smart Systems Integration)	Prof. T. Gessner, Prof. S. Rzepka, Prof. T. Otto	members of the steering group
Eureka Cluster 'Metallurgy Europe'	Prof. S. Rzepka	working group leader
European Center for Micro- and Nanoreliability (EUCEMAN)	Prof. B. Michel Prof. S. Rzepka, Prof. B. Wunderle, J. Hussack	president committee members
EuroSimE, Bordeaux, France	Prof. B. Wunderle, Dr. R. Dudek	members of the conference committee
German Science Foundation	Prof. T. Gessner	referee
Humboldt Foundation	Prof. B. Michel	referee
HTA	Dr. D. Vogel	Member, Reliability Track
ICECS 2014	Dr. C. Hedayat	referee
International Conference ICEPT, Shanghai, China	Dr. J. Auersperg	technical committee member
International Conference IPTC, Singapore	Dr. J. Auersperg	technical committee member
International Conference on Planarization/CMP Technology	Dr. K. Gottfried	program committee member
IS&T – Society for Imaging Science & Technologies	Prof. R. R. Baumann	vice president
ITherm Conference	Prof. B. Wunderle	program committee member
Large-area, Organic and Printed Electronics Convention	Prof. R. R. Baumann	scientific board and advisory board
laser optics Kongress "Optische Sensorik und Cyber-Physical Systems"	Prof. T. Otto	member of program committee
LEIBNIZ CONFERENCE OF ADVANCED SCIENCE	Prof. T. Otto	member of program committee
Materials for Advanced Metallization MAM	Prof. S. E. Schulz	member of scientific program committee
MEMS Industry Group, Executive Congress Europe	Dr. M. Vogel	committee member
MEMUNITY	Dr. S. Kurth	member of executive committee
Microsystems Technology Journal	Prof. B. Michel	editor-in-chief
Materials Research Society (MRS)	Prof. R. R. Baumann, Dr. A. Willert, Dr. T. Blaudeck, Dr. S. Hermann	member
MWSCAS 2014	Dr. C. Hedayat	referee
National Research Agency, France	Prof. B. Michel	referee
NEWCAS 2014	Dr. C. Hedayat	referee
Organic Electronics Association (OE-A)	Prof. R. R. Baumann	member of the board
SEMICON Europa	Prof. T. Gessner, Dr. M. Vogel	program committee members of MEMS conference
Smart Systems Integration Conference	Prof. T. Gessner	conference chair
Smart Systems Integration Conference	Prof. T. Otto, Prof. B. Michel, Dr. C. Hedayat, Prof. K. Hiller, Prof. S. Rzepka, Prof. R.R. Baumann	members of program committee
Therminic Workshop	Prof. B. Wunderle	conference chair

Memberships of Fraunhofer ENAS

ALD Lab Dresden	Dresden, Germany
Cool Silicon e. V.	Dresden, Germany
Dresdner Fraunhofer-Cluster Nanoanalytik	Dresden, Germany
Elastopôle	Orléans, France
Elektronik-Forum OWL	Paderborn, Germany
Eureka Cluster 'Metallury Europe'	Ulm, Germany
European Center for Micro and Nanoreliability EUCEMAN	Berlin, Germany
European Platform on Smart Systems Integration EPoSS	Berlin, Germany
Fraunhofer-Cluster 3D-Integration	Dresden and Chemnitz, Germany
Fraunhofer-Verbund Mikroelektronik	Germany
Fraunhofer-Allianz Nanotechnologie	Germany
Fraunhofer-Allianz autoMOBILproduction	Germany
Industrieverein Sachsen 1828 e. V.	Chemnitz, Germany
innoZent OWL e. V.	Paderborn, Germany
It’s OWL Intelligente technische Systeme Ostwestphalen/Lippe e. V.	Bielefeld, Germany
IVAM Microtechnology Network	Dortmund, Germany
MEMS Industry Group®	Pittsburgh, USA
Nano Technology Center of Competence “Ultrathin Functional Films”	Dresden, Germany
Organic Electronics Association OE-A	Frankfurt/Main, Germany
Organic Electronics Saxony e. V. OES	Dresden, Germany
Semiconductor Equipment and Materials International (SEMI)	San Jose, USA
Silicon Saxony e. V.	Dresden, Germany

PUBLICATIONS (SELECTION)

BOOKS

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