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Topic       Printed Electronics at Technische Universität Darmstadt
Cover      3D view of inkjet printed Technische Universität Darmstadt logo recorded by white light interferometry
Welcome

The nineteenth century was the time of black and white printing. The twentieth century was one of color printing. Now - in the century of printed electronics - researchers from Technische Universität Darmstadt are revolutionizing printing technology.

Located in the metropolitan region of Rhein-Main-Neckar, one of the most dynamic and economically robust regions in Europe, Technische Universität Darmstadt is the scientific and cultural heart of Darmstadt – called the City of Science. As one of Germany's leading technical universities, Technische Universität Darmstadt's main focus is engineering science, based on natural sciences, supported by the humanities and social sciences. It enjoys an excellent reputation worldwide in teaching and scientific research.

Regarding paper and printing one important and challenging research topic at Technische Universität Darmstadt is Printed Electronics. Our university strives to provide international excellence in the field of Printed Electronics. With emphasis on technology, engineering, and natural sciences Technische Universität Darmstadt has established a close collaboration amongst its various departments, with strong emphasis on research across the boundaries between the various disciplines. As a result of the interdisciplinary cooperation between material science, mathematics, physics, chemistry, mechanical and electrical engineering, Technische Universität Darmstadt has established a Competence Center of Printable Electronics.

The Competence Center of Printable Electronics of Technische Universität Darmstadt is more than a collaboration of several institutes and groups of our university. The Competence Center is a significant source of innovation and scientific research. As an excellent pivotal point in Printed Electronics the Center offers access to a complex spectrum of unrivaled experience and high-tech equipment of Technische Universität Darmstadt, which is able to identify and solve scientific challenges.

Since 2010 Technische Universität Darmstadt is part of LOPE-C – an important, international conference of Printed Electronics in Frankfurt. Focused on developing new technologies and applications in Printed Electronics, Technische Universität Darmstadt is successfully strengthening its international connections through the exchange and presentation of the latest trends, technologies and solutions in research and development.

I wish the Competence Center of Printable Electronics and all involved groups of Technische Universität Darmstadt all success.

Prof. Dr. Hans Jürgen Prömel
President of Technische Universität Darmstadt
Technische Universität Darmstadt

Technische Universität (TU) Darmstadt is one of Germany’s leading technical universities. Its around 270 professors, 3,850 employees and 23,000 students devote their talents and best efforts to the significant future research fields: energy, mobility, communications and information technologies, housing and living conditions. The wide variety of disciplines represented are all focused on technology, as viewed from the vantage point of engineering, the natural sciences, the humanities, and the social sciences. This covers the full range of academic endeavor, from the origination of basic concepts to practical, everyday applications.

The TU Darmstadt is Germany’s first autonomous university and has a state-funded budget of 269 million Euros (2009, incl. building funds). Its capacity for innovation is evidenced inter alia by the steady growth in annual funding received from outside sources. In 2010, 139 million Euros were contributed by industry, the German Research Foundation, and the European Union for 2010. This makes TU Darmstadt one of Germany’s leading academic recipients of outside funding. In renowned rankings by the Deutsche Forschungsgemeinschaft, the Alexander von Humboldt Stiftung, and the Zentrum für Hochschulentwicklung, as well as polls of the personnel directors of major corporations, it has consistently corroborated its leadership in research, academic excellence, and its qualification of graduates for top jobs and successful careers.
Printable Electronics at Technische Universität Darmstadt

The intention of this brochure is to provide an insight into an attractive research network at TUD: the Competence Center Printable Electronics. Based on a long research tradition in the disciplines of inorganic and organic chemistry, material sciences (OLED, organic TFTs, OPV, material surfaces, ceramics), mechanical engineering (printing technology) and electrical and information engineering (semiconductor technology and electronics), in 2005 the existing research competences have been joined in a Competence Center with the objective to address new research challenges in the field of Functional Printing and printable electronics. The involved groups of TU Darmstadt perform the complete process chain of Functional Printing, from material and substrate development and characterization, over design of devices and production, to device development and characterization and simulation (see figure on p. 10).

Research objectives

The following research objectives are targeted in joint research and industry projects:

• Organic Light Emitting Diodes (OLEDs)
• Organic Photovoltaics (OPV)
• Organic and inorganic semiconductor materials for thin film transistors (TFTs)
• New printing technologies and improvement of existing printing technologies for Functional Printing
• Mechanical stress analysis and modelling of printed multi-layer structures
• Electronic device and circuit modelling, simulation and design
• Recycling of mass-printed electronics

Besides many very directed bilateral industry projects and public funded research projects on partial aspects of the overall topic, a joint research lab has been set up successfully with Merck KGaA (Merck-Lab). Furthermore, TU Darmstadt is partner in the Spitzencluster “Forum Organic Electronics” and supporting the “Innovation Lab GmbH” (iLab) in Heidelberg.

Cooperations in Printable Electronics

TU Darmstadt is open for any industry and research cooperation in the fields mentioned above. We believe that success in the field of printable electronics is strongly dependent on cooperation capabilities of partners, which are willing to cross-link their know-how in order to multiply it. Our intention is to be an excellent and reliable research partner, wherever we can contribute our expertise and we strongly encourage other research networks, institutions and companies to get in touch with us.
Functional Printing at IDD – Institute of Printing Science and Technology

Printing of electronics – an economic challenge

Today, electronics are based on silicon technologies. Almost every electric device or machine available on market contains a silicon chip which attributes some type of intelligence or contributes to user communication. Much of this technology relies on silicon, i.e. on chips contained in these devices. By printing and integrating organic electronic materials in devices, completely new applications may be developed. In future, it will be possible to produce RFID tags, air and train tickets, price labels etc. which contain electronic functionality at low cost levels which are inaccessible for the traditional chip technology. Mass printing processes permit an economically reasonable relation of device value and production cost. It is the aim of the research groups at Technische Universität Darmstadt to develop technical solutions for this new technology, focusing on material design, printing process and their integration into new innovations.

Printed electronics – the scientific challenge

For the production of printed OLEDs, OFETs, memory elements, RFID devices, sensors or displays a large variety of different materials is required: organic semiconductors, light emitters, dielectrics, battery materials, substrates,
sealants, transparent conductors and sensor materials. Moreover, these materials must be processed in a way to create extraordinarily thin layer stacks in the final device, with extremely high surface quality. Reliable processing techniques such as printing, coating and vacuum deposition techniques have to be improved for this purpose. Simultaneously with the development of adequate functional materials, efficient electronic circuits have to be designed. The focus of the research groups at Technische Universität Darmstadt is not only the optimization of electronic material parameters. Rather, the processability of these materials in a solution based printing or coating process is also a challenging scientific topic, requiring the competences in mechanical engineering, fluid mechanics, and printing science.

**TUD - the research network**

Technische Universität Darmstadt combines a network of research institutes and collaborations in electrical and mechanical engineering, chemistry and material science enabling an interdisciplinary research in this new field of technology. The competences range from chemical material synthesis to device design and characterization, process development.
and product lifetime analysis. The institutes work together in order to make electronics truly “printable”.

**IDD - institute of printing science and technology**

Scientific competences for large area printing are focused at the Institute of Printing Science and Technology (IDD). IDD possesses competences in offset, gravure, flexo and screen printing and the required machinery from lab to production scales. Within Technische Universität Darmstadt, the IDD is also a research platform for testing the printability of different functional materials and their combination and integration into standard industrial graphical printing and manufacturing processes.

Functional Printing, i.e. the printing of electronic devices, imposes high demands on materials and printing processes. In spite of the very different physical and chemical nature of the materials, all of them must be transformed into a fluid which is processable in a printing press. The printer must be able to produce stacks of extremely homogeneous, defect-free, ultra-thin layers with a thickness of a few 10 nm each - the 5,000th fraction of the thickness of a human hair. The extreme thinness of the electrically active layers is dictated by the physics of charge carrier transport in organic semiconductors and a crucial feature of printed electronic devices with a good performance. Even if the printing process of these layers has been realized, the design of reasonably small, reliable and powerful OFETs, complex memo-
ries or sensor elements is still a formidable task. Interdisciplinarity of research has a long tradition at Technische Universität Darmstadt. It has already been proven to be the right recipe for a successful research within a competitive and rapidly developing field of printed electronics. Therefore the Institute of Printing Science and Technology is embedded in an environment of active research groups and institutes.

IDD is part of numerous research cooperations in printed electronics, partly under participation of worldwide leading enterprises. Moreover, IDD is the interface of the printed electronics research at TUD to the Spitzencluster “Forum Organic Electronics” which resides at the InnovationLab GmbH in Heidelberg, a research initiative funded by the Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research).

This brochure is intended to introduce the research institutes at the Technische Universität Darmstadt with competences and activities in printed electronics.

For more information

Institute of Printing Science and Technology
Prof. Dr.-Ing. Edgar Dörsam
Dr. Hans Martin Sauer
www.idd.tu-darmstadt.de
The involved groups of TU Darmstadt will be presented in the order of the process chain for Functional Printing.
ICG
Inorganic Chemistry Group

Eduard-Zintl Institute for Inorganic and Physical Chemistry

About Us

The research of the Inorganic Chemistry group (ICG) at the Eduard Zintl-Institute at TU Darmstadt focuses on the area of inorganic functional materials. We synthesize, characterize and study the properties of carbon nanomaterials (carbon nanotubes CNTs, graphene) and metal oxides (e.g. of transition and main group metals: Zn, Hf, Zr, Fe, Ce, Ga, In) as advanced materials in electronic devices (e.g. transistors, catalysts, sensors and printable electronics). With respect to printing, we are currently working in the area of Functional Printing of CNTs and nanostructured metal chalcogenides (TCOs, CIS, CIGS).

Research Concept of the Inorganic Chemistry Group

Our main research interest is to synthesize new materials with exceptional new functional properties. We are aiming to incorporate materials like CNTs, graphene and metal oxides in device structures like field effect transistors (TFTs), sensors or catalysts. From a fundamental point of view we are trying to understand the general concepts which rule their functional properties. Characterization with current state of the art spectroscopic and microscopic techniques is another research field. This allows us to gain a most complete figure of the new materials properties and to understand their properties in depth. Our research concept relies on a strong interdisciplinary approach and project work between groups from academia and industry with complementary research interest and expertise is central to our research.

Research Area Functional Inorganic Materials

The research field of printable electronics is concerned with the manufacturing of electronic circuits and devices by means of printing technology. The necessary conditions in this technology define a challenge for the printing of inorganic materials. The use of soluble molecular precursors, which can be transformed into active functional materials by the use of facile, low temperature routes are in the focus of our research in the area of printable electronics. Herein, molecular single source precursors are of great importance. We have developed a new approach to the low temperature processing of printed inorganic functional thin films of several main groups and transition metal oxides using such molecular precursor complexes.

Contact

Eduard-Zintl-Institut
Inorganic Chemistry Group
Prof. Dr. Jörg J. Schneider
www.chemie.tu-darmstadt.de/schneider
About Us

The Advanced Thin Film Technology group (ATFT, Fachgebiet Dünne Schichten) develops new thin film deposition methods for functional materials. The focus is on physical vapor deposition (PVD) techniques such as advanced oxide molecular beam epitaxy (ADOMBE), advanced pulsed laser deposition (PLD), and sputtering techniques. The materials in focus are mostly functional oxides such as high-temperature superconductors, magnetic materials and high-k dielectrics.

Research Concept of ATFT

Our research concept is twofold. We are developing the thin film technology itself in order to find controlled ways to grow complex systems consisting of different elements and layers of different materials. In particular, we have combined in-situ a unique oxide molecular beam epitaxy system with a pulsed laser deposition chamber. Having the most advanced thin film technologies at hand, we are focusing on new metastable materials, new heterostructures, and improved materials which are already in use. One key issue is the control of oxygen content in different material systems where oxygen vacancies influence greatly the materials properties such as conductivity, insulation, heat transport, superconductivity and magnetism.

Research Area Functional Oxides

Functional oxides are in the center of so-called oxide electronics, which is an upcoming research area with applications in many fields as energy materials, spintronics, superconductivity, sensors, and adaptive materials. Recent materials investigated in our group include the high-k dielectric HfO$_2$, new pnictide superconductors, tunable materials for microwave components such as (Sr,Ba) TiO$_3$, transparent conducting oxides such as (Zn,Al) O, magnetic materials for spintronics, as for example Fe$_3$O$_4$ and perovskite-type oxides. The group is also working on piezoelectric thin films for use in the new field of adaptronics. One hallmark of oxide electronics is, that many of the mentioned materials can be combined in heterostructures to create hybrid materials with novel properties such as multiferroic behavior.

Contact

Advanced Thin Film technology Group
Prof. Dr. Lambert Alff
www.mawi.tu-darmstadt.de
About Us

The research of the Electronic Materials Department (e-mat) of the Materials Science Institute at Technische Universität Darmstadt is based on the investigation of the electronic properties of functional materials and the impact of these properties on technologically relevant applications. The e-mat group introduces the electrical functionality of materials to the field of materials science.

The manifold experimental characterization units giving access to the elemental electrical and optical properties of the involved functional materials provide the basis for the detailed analysis of the device functionality. To bridge the fundamental material properties and the device performance, theoretical simulations are performed giving a detailed insight into the devices.

Generally, the e-mat group deals with three main topics: optoelectronic properties of organic semiconductors, charge and polarization in dielectrics and luminescence in inorganic phosphors.

Research Area Organic Semiconductors

The investigation of organic semiconductors in technologically relevant applications such as organic light emitting diodes and organic thin film transistors is the central aspect in the area of optoelectronic properties in organic semiconductors. The aim is to further understand the function of organic materials in devices and to identify bottlenecks for a boost in device performance. Above all, e-mat’s approach opens ways to novel devices with unusual performance.

The production of organic devices reaches from wet processing to vacuum deposition techniques while the e-mat laboratory provides elaborated techniques for the material and device characterization. The pool of complementary characterization techniques enables us to determine various material parameters such as the electronic state distribution or the charge carrier mobilities. Integral and local measurement setups are installed. To classify the investigated devices several AC, DC and transient methods are available.

Contact

Electronic Materials Department
Prof. Dr. Heinz von Seggern
www.mawi.tu-darmstadt.de/em
Research Focus

Our research interest is focused on fundamental research on organic functional device structures as light emitting diodes and solar cells. Characterization of bulk materials and interfaces using photoelectron spectroscopy is of utmost importance to derive and test optimization strategies. Basic questions, concerning bulk properties as doping as well as structural and electronic interface properties are investigated. Fundamental mechanisms of contact formation and interface modifications are studied to optimize hetero-junctions for advanced device applications. In addition interfaces of organic semiconductors and inorganic contact materials as metals and transparent conductive oxides are studied. Besides the activities on organic materials, intercalation compounds, electrochemical phase boundaries, and composite structures are investigated in the surface science department. The applications in general aim at organic electronics especially renewable energy systems as organic and thin film photovoltaic converters, synthetic fuel production, and Li ion batteries.

Research Concept

For the microscopic analysis of interfaces a variety of surface science techniques especially photo electron spectroscopy is applied to samples prepared and processed under defined conditions in integrated ultra high vacuum (UHV) chambers (cluster tools). The group has developed the know-how to integrate technologically relevant processes in UHV as well as ex-situ with extremely surface sensitive analysis methods. Physical and chemical evaporation methods and even wet chemical bath deposition are routinely applied. The spectroscopic analysis of phase boundaries is complemented by ex-situ measurements of e.g. current voltage curves of device structures. Aim of the work is the correlation of interface properties with device properties.

Contact

Surface Science Department
Prof. Dr. Wolfram Jaegermann
Dr. Thomas Mayer
www.tu-darmstadt.de/fb/ms/fg/ofl
NAW
Ceramics Group

Processing of Oxide Coatings for Inorganic Electronics

About Us
The scientific effort in the Ceramics Group is focused on the following topics:
• Processing and sintering of oxides (in bulk and layer form)
• Development of new piezoceramics
• Electrical properties of ferroelectrics
• Mechanical properties of ceramics, composites, ferroelectrics

Our Approach
Emphasis is put on the correlation between microstructure and mechanical as well as functional properties. A number of processing methods are available in order to manufacture different microstructure classes, to determine their specific properties and to rationalize these with straightforward modelling efforts. Thus, materials optimization is possible allowing effective interplay between processing, testing and modelling. In particular, new lead free and high temperature piezoceramics can be obtained and extensively characterized electrically and mechanically.

Ceramic Film Processing
Our activities related to ceramic layer processing include deposition of continuous or patterned films from suspensions (by tape casting, spin coating, soft micromolding...), drying and sintering. Characterization tools including laser dilatometry allow to measure densification in-situ and provide constitutive data to be implemented in predictive models. Microstructure is thoroughly quantified to highlight changes during constrained sintering and correlated to the functional properties. Furthermore, measurement of dielectric and ferroelectric properties of functional materials (newly processed or cyclically fatigued) as function of temperature and frequency is available at our institute.

Contact
Ceramics Group
Prof. Dr. Jürgen Rödel
www.mawi.tu-darmstadt.de/naw
About Us

The Institute for Paper Technology was founded in 1905 and is the oldest research institute worldwide focused on paper manufacturing and paper recycling. Today, PMV has approx. 40 employees and comes with a well equipped paper laboratory and a pilot plant for paper recycling.

Research Topics

The research at PMV covers the areas of paper recycling and recycling processes, chemical constituents and process water treatment in paper production, as well as paper physics and associated measurement technologies. Projects within these research areas are primarily concerned with topics such as separation of particles from fibre suspensions based on physical properties like flexibility. Other topics are recyclability of paper products due to application of suitable printing inks and adhesives, anaerobe water treatment, functional paper products based on encapsulated active agents, as well as measurements of physical properties of paper and fibre suspensions with high resolution image analysis.

Relation to Printed Organic Electronics

Environmental sustainability and recycling issues are an inherent part in the project “Printed organic circuits and chips” (Polytos), which has been launched by the Spitzencluster “Forum Organic Electronics” (DaVinci). Within the framework of Polytos, PMV studies the effect of printed organic electronics on the paper chain by assessing the recyclability of paper products with attached smart labels. The recyclability topic comprises the behavior of labels in the repulping process, the separation / deposition of label fragments and peeled off components, as well as the identification of undesirable constituents.

PMV developed a test method providing a realistic simulation of the treatment within the principal recycling processes for packaging paper and board. Tests in laboratory scale on dummy labels demonstrate that substances can be detached from the label. These substances will follow the pulp stream and may accumulate in the paper chain.

Contact

Paper Technology and Mechanical Process Engineering
Prof. Dr.-Ing. Samuel Schabel
www.pmv.tu-darmstadt.de
About Us
At the Institute of Printing Science and Technology (IDD: Institut für Druckmaschinen und Druckverfahren), the focuses of research lie in the areas of mechanical and process engineering as well as applied economics, accompanying the rapid development in the fields of printing machine engineering and print media.

Research Concept of IDD
Our research concept is to make a significant contribution to the understanding of printing processes.

The research activities are generally based on an interaction between theory, modelling, simulation and experiments. Existing systems and processes are analyzed and theoretical and experimental studies will be fundamentally described by a model. Simulations allow calculations and predictions.

Research Area Functional Printing
Our Institute has three research areas: Color, Material and Technology and Functional Printing. The area of Functional Printing analyzes the printing processes in terms of their suitability for functional materials and their further development. The printing laboratory has a three-stage structure and all current processes such as offset, gravure printing, screen printing, flexography and inkjet can be studied. At the first step the printability of functional materials can be tested and at the second step printing formats up to size DIN A4 are available. All these printing studies can be carried out in a climatized laboratory. In addition, the functional materials can be tested at the Gallus RCS 330-HD in all current printing processes by roll to roll. Extensive laboratory equipment for analyzing homogeneity, wetability, curing, rheology and topography is available.

Contact
Institute of Printing Science and Technology
Prof. Dr.-Ing. Edgar Dörsam
Dr. Hans Martin Sauer
www.idd.tu-darmstadt.de

Screen printed electroluminescent panel produced at IDD which consists of up to 7 layers of different functional inks.

Contact
Institute of Printing Science and Technology
Prof. Dr.-Ing. Edgar Dörsam
Dr. Hans Martin Sauer
www.idd.tu-darmstadt.de

Flexographic printing plate and printing substrate with functional patterns.
About Us

The focus of research of the Institute of Structural Mechanics is on modelling, analysis and assessment of mechanical structures and their best possible improvement using algorithmic optimization. Almost every product of mechanical engineering can be regarded as a mechanic structure, so the Institute of Structural Mechanics calls a wide and profound area of applications its own. This area ranges from classical metallic machine elements to modern, highly stressed, composite lightweight constructions.

Research Concept of FSM

The key task of our research is to improve the basic understanding of mechanic structures. The general approach is shortly briefed. First, a model of a mechanic structure is built. Subsequently, approved methods like the finite element method are applied or new, better adapted methods are developed, to assess highly stressed areas in the analyzed structure. Finally, the functionality as well as the reliability of the investigated mechanic structure shall be increased using the potential of design optimization.

Key aspects of our research are the modelling and analysis within structural and composite mechanics. Particularly, the precise ascertainment of special composite effects like the free edge and the free corner effect as well as coupling effects are in the spotlight. A further research activity of FSM is the applied structural optimization within lightweight constructions. Furthermore, the FSM is engaged in the implementation of kinematic coupling equations in the scaled boundary finite element method and the development of a source code for the application of the scaled boundary finite element method in composite mechanics.

Research Area Functional Printing

Within the research activities in Functional Printing, the FSM is engaged in the modelling and analysis of printing processes. From a mechanical point of view, printed structures can be regarded as layered composites. In these composites, stress concentrations arise due to the mismatch of the material properties of the applied materials. The assessment of the failure criticality of these stress concentrations, which can cause delaminations and crack formations, are the key task of our research activities in Functional Printing.

For the assessment of the failure criticality straight cracks emanating from the origin of the stress concentrations are introduced. Finally, the energy release rate is calculated and the affinity to delaminations is evaluated using the fracture toughness of the interface.

Contact

Institute of Structural Mechanics
Prof. Dr.-Ing. W. Becker
www.fsm.tu-darmstadt.de
About Us

Three groups build up our institute:

• Microtechnology and Electromechanical Systems (M+EMS), Prof. Dr.-Ing. Helmut F. Schlaak
• Measurement and Sensor Technology (MuST), Prof. Dr.-Ing. Roland Werthschützky
• Lighting Technology (LT), Prof. Dr.-Ing. Tran Quoc Khanh

Since 2003, the „Laboratory of Lighting Technology“ is part of the institute. The research topics are the development and characterization of light emitting diodes (LED), organic LEDs, their electrical periphery and diverse applications like automotive and interior lighting.

The laboratories M+EMS and MuST work very closely in several projects. Their research is concentrated on micro-nano-integration, microtechnology and the relating applications like microactuators, microsensors and micro-electromechanical systems. The requirements on functional principle and packaging are mainly deduced from medical and industrial applications. The main focus lies on mechanical quantities like pressure, force, strain and torque. The analyzed transducer principles are piezoresistive, capacitive, piezoelectric for both sensors and actuators and electrostatic.

Research Area Functional Printing

The core competence of our institute is the development and thus the integration of components and systems in micromachining technologies. Functional Printing is the consequential extension of the manufacturing technologies for rapid prototyping or low cost transducers. In line with the LOEWE Center AdRIA, structural integrated strain sensors, piezoelectric actuators and DEAs are developed to monitor or even reduce noise-causing vibrations in any systems.

Contact

Institute of Electromechanical Design
Prof. Dr.-Ing. Helmut F. Schlaak
www.institut-emk.de
IES
Integrated Electronic Systems Lab

Design, Modeling and Simulation of Integrated Electronic Circuits and Systems

About Us
The Integrated Electronic Systems Lab (IES) and the Microelectronic Systems Research Group (MES) focus research on analog and digital circuits and systems and related electronic design automation. Currently, the main research focus is on Systems-on-Chip, Systems-in-a-Package, Scalable Memory Architectures and Circuit Design for New Evolving Technologies. Our know-how is in the thorough understanding of the complete design and verification flow for integrated electronic circuits and systems, from single transistor to system-on-chip level using modern sub-micron semiconductor technology processes.

Device Modelling and Circuit Design for New Evolving Technologies
Functional Printing can lead to a new way of fabricating integrated electronic circuits and systems. We are conducting research on device modelling based on organic and inorganic functional materials and resulting circuits. Device modelling and circuit design is different from established classical silicon based technologies due to rough surfaces and large process variations. A new paradigm for modelling, design, optimization and verification is required for these new evolving technologies. This approach has to incorporate a thorough material, technology, device, circuit and layout understanding in order to lead to commercial relevance.

Research Objectives
Our goal is to contribute to a universal design and fabrication flow for Printable Electronics. Therefore models for integrated passive and active devices have to be provided in order to meet the application’s requirements on accuracy. This requires accurate device models which reflect physical properties of the processed materials and the impact of processing steps and resulting morphologies on the electrical device parameters.

Contact
Integrated Electronic Systems Lab
Prof. Dr.-Ing. Klaus Hofmann
Prof. Dr. Dr. h.c. mult. Manfred Glesner
www.ies.tu-darmstadt.de
About Us
At the Microwave Engineering Group (MWT: Mikrowellentechnik), the research activities cover a wide range of microwave and millimeter-wave electronics, i.e. in the frequency range from MHz up to THz. Using novel approaches, functional materials and innovative technologies, our application-oriented research focuses on advanced tunable, reconfigurable and energy-efficient microwave components, with which we endeavor to cope with emerging demands in wireless communications, navigations, sensing and imaging.

Research Methodology
Through years of active interdisciplinary research in applying novel materials in microwave technologies, a multi-scale approach has been established. It covers a comprehensive chain of innovation from material synthesis, processing technologies, component design, system architecture, simulation and characterization tools across the levels. Beside fundamental research, we also engage in turning the academic innovations to commercial potentials.

Emerging Technology: Low-cost Printed Microwave Electronics
Recently, low-cost and energy-efficient wireless modules are attracting significant research efforts. Potential applications can be sensing and identification for e.g. industry, medicine and security. Their complexity and cost margin are stringent, while the novel functionalities are demanded. Therefore, our research focuses on functional materials deposited by various printing methods. It starts from optimization of oxides and liquid crystals for target applications. Then, dedicated printing technologies, e.g. screen printing, inkjet printing and spin coating, are evaluated and adapted with a balance consideration of substrate compatibility, metallization integration, producibility. Afterwards, new component concepts are simulated, and efficient design methodologies are investigated. They are prototyped in our clean room microfabrication facility. Finally, in-house characterization methods provide in-depth evaluation of materials, interfaces and components.

Applications
- Microwave RFIDs & Sensors
- Phased Arrays
- Tunable Multiband Antennas
- Integrated Tunable Passives, e.g. varactors, phase shifters, matching networks, filters

Contact
Microwave Engineering Group
Prof. Dr.-Ing. Rolf Jakoby
www.mwt.tu-darmstadt.de
Research Projects

BMBF Projects

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<td>Photoelectron spectroscopic analysis of energy converting interfaces of organic and dye sensitized solar cells</td>
<td>BASF, BOSCH</td>
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<td>LUMOLED</td>
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<td>LIQUIDA</td>
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<td>OPV-Hybrid</td>
<td>Organic-inorganic hybrid-structures for photovoltaics</td>
<td>Universities Oldenburg, Erlangen, Würzburg and Berlin, Helmholtz Center Berlin</td>
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<tr>
<td>TOPAS 2012</td>
<td>Theoretical description of tunnel junction and CGLs</td>
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LOEWE Projects

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<td>AdRiA</td>
<td>Adaptronic Research Innovation Application</td>
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Industry Projects

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<td></td>
<td>Several projects with Heidelberger Druckmaschinen, Schenk Process, Schott, EADS, PolyIC</td>
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# Research Projects

## Spitzencluster Forum Organic Electronics

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<td>MESOMERIE</td>
<td>Morphology and Electrical Structure of Organic-Organic and Organic-Metal Oxide hybrid Systems</td>
<td>University of Heidelberg, University of Braunschweig</td>
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## EU Projects

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<tr>
<td>ACE</td>
<td>Antenna Center of Excellence</td>
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<tr>
<td>ARASCOM</td>
<td>MEMS &amp; Liquid Crystal based Agile Reflect-arrays for Security &amp; COM</td>
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## DFG Projects

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<th>PROJECT</th>
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<td>TICMO</td>
<td>Tunable Integrated Components in Microwave Technology and Optics</td>
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Equipment

IDD

The printing equipment of the IDD laboratory includes the most common printing processes such as offset, gravure, screen, flexographic and inkjet printing as well as embossing and coating techniques. Taking account of testing small-volume and production-related conditions a three level approach is implemented. The first level consists of printability testers that are used for simple tests handling different kinds of rigid and flexible substrates. The advantage of these machines is the ability of using very small amounts of liquids and substrates to understand the desired processing technique qualitatively.

The second level involves laboratory printing machines (sheet-to-sheet and roll-to-roll) with substrate widths of up to 210 mm. Here, minimum fluid amounts of less than 100 ml are required. A deeper understanding of upscaling the processes according to sheet conveyance and continuous printing can be achieved. The printing tests of levels 1 and 2 can be performed either in our laboratory under UV-protective conditions, or in a climatized laboratory with additional environmental control. The third level provides a production-environment, in which processes can be tested on a modified roll-to-roll production machine. For this purpose, amounts of fluid in the liter-scale and substrates in reel are required. The printing press is configured for the special task of printing functional structures. The available printing units for flexographic, gravure, screen, offset and ink jet printing can be simultaneously implemented and changed in their order. All printed samples can be cured by UV, hot air, and IR respectively. A wide range of measurement instruments allow the characterization of inks and substrates according to e.g. shear and extensional viscosity, particle size, surface tension and wetting behavior. Samples, parts, and components can be tested for tensile, compression, and bending stresses. For the morphological characterization of substrates, printing results, anilox rollers, gravure cylinders and flexo plates the IDD uses standard measurement devices for printing processes and a wide range of optical (up to 100x) and tactile (AFM) microscopes. These include an optical profilometer that combines confocal and interferometric microscopy also with the tactile method of atomic force microscopy in a single tool. With this tool three-dimensional surface determination with a vertical range of below one nanometer is feasible.
Equipment

**e-mat**

Research equipment on the institute involves production and characterization lines for OFETs and OLEDs. Several nitrogen filled glovebox systems are installed to allow for an inert sample production and characterization. A shuttle system interconnects all systems inertly. The production boxes contain wet processing methods and vacuum deposition chambers. The characterization boxes allow for standard IV-characterization, impedance spectroscopy and transient electrical measurements even at low temperatures.

low-temperature AFM allows for a local determination of electrical parameters even under device operation. A pulsed laser system with a wide wavelength range allows to determine excitation lifetimes or charge carrier transient times. The system consists of a Nd-YAG Laser with OPO and Ti-Saphire laser. Time and spectral resolved light detection is performed with a combination of an OSMA with a monochromator. A TSD/TSL setup for the determination of density of state distributions of trap states is available. Frozen charges in trap states are liberated by temperature increase causing a measurable current. The dependence of the thermally stimulated current on the temperature is a signature of the charged DOS. Besides, the system allows for a temperature dependent determination of the conductance down to He temperatures. An absorption and reflectance spectrometer is combined with a fluorometer, a portable CCD

spectrometer and a FT-IR spectrometer. A spectral resolved ellipsometer is available to determine the dispersion of the complex reflection index and to non-destructively measure layer thicknesses of thin-film stacks.

**ICG**

ICG is involved in several research projects in academia and industry. Covered research topics are material development for gas sensors, pressure sensors and field effect transistors. Research equipment involves wet chemical synthesis technique also under anaerobic conditions, chemical vapor deposition equipment, electrochemical synthesis equipment, plasma surface equipment, surface analysis techniques (BET), dynamic light scattering for particle size determination and atomic force microscopy (AFM).
Equipment

Surface Science Department

In order to obtain contamination free results, thin film preparation and surface analysis using photoelectron spectroscopy are integrated in a cluster of ultra high vacuum chambers. Each of the processes necessary for the production of full device structures is applied in a separate UHV-chamber to avoid cross-contamination. The group runs three additional integrated systems: DAISY-FUN for Fundamental Research, DAISY-MAT for Materials Science and SoLiAS for Solid Liquid Interfaces Analysis at the Synchrotron BESSY in Berlin.

MWT

RF-measurement equipment at the institute involves HP spectrum analyzers up to 40 GHz and vector network analyzer Anritsu 45 MHz-110 GHz, on-wafer probe station, different signal sources from 0.1 to 94 GHz, power meter up to 65 GHz plus antenna measurement and material characterization equipment. Component technologies involve sputtering chambers, plasma etching and deposition (RIE + PECVD), photolithography processing line, galvanic photo-resist development, transmission electron microscopy and THz and optics labs in a 150 m² clean room. The simulations can be arranged with commercial tools: e.g. CST Microwave Studio, Agilent ADS, Ansoft Designer and Microwave Office, or with proprietary tools: FDTD solver for nonlinear composite-multilayer structures.

EMK

Research studies at the institute involve professional state-of-the-art analyses, deduction of requirements, preparation of concepts for implementation, functional analyses and characterization of micro- and precision engineering assemblies. Mechanical assembly and fabrication of micro components are done in the appendant clean room and air-conditioned laboratory. It is split into two sections: Photolithography, electroplating and etching processes are conducted under yellow lighting. The second section is used for vacuum deposition (PVD, sputtering), dry etching (RIE), assembly, as well as measuring and inspection. A workshop for precision engineering supports the research activities. Finally, a unique production line for stacked dielectric elastomer actuators (DEA) with automated fabrication and characterization is part of the institute. In cooperation with other institutes or companies, processes like e.g. ion implanting are realized. With diverse precision measurement setups, e.g. force measuring set-up, motion analyzer for MEMS and with six DOF, flow sensor testing set-up, piezoelectric beam bending actuator, the characterization of the described components and systems can be performed.
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