CeOPP

2012
2013

Center for Optoelectronics and Photonics Paderborn

Preface

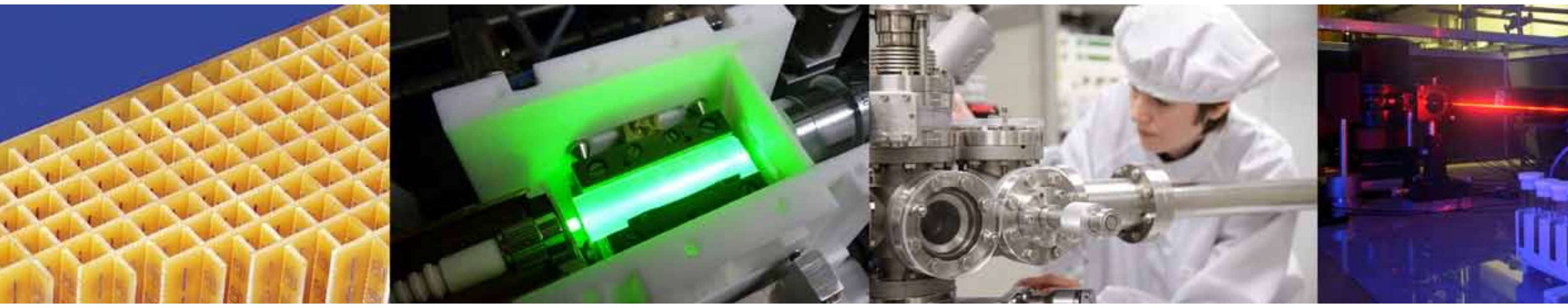
The University of Paderborn is well known as "The University of the Information Society". Corporate Image, mission statement and all university activities aim towards this core competence. With its focus on computer sciences and its applications the University of Paderborn concentrates on the requirements of the Information Society. In accordance with this guiding principle the University of Paderborn perceives itself as a research university.

Optoelectronics and photonics are significant areas of research within our university. With the foundation of the central research facility "Center for Optoelectronics and Photonics Paderborn" (CeOPP) in the year 2006, the joint research activities in the fields of optical technologies became a sustained topical focus of the University of Paderborn. Within the CeOPP, 15 groups from the departments of physics, electrical engineering and chemistry are currently successfully collaborating in research and teaching. They develop novel devices and circuits based on emerging technologies in optoelectronics and photonics, and demonstrate their performance in sophisticated device applications. With the opening of the new building for optoelectronics, integrated optics, and photonics in 2006, excellent lab and cleanroom facilities were made available to our scientists. Another important prerequisite for success is a good mixture of highly qualified young as well as experienced researchers, who guarantee constant progress and improvement. The University of Paderborn intends to continue to promote and set on this field of research through further recruitments of qualified researchers. The recently established DFG Research Training Group "Micro- and Nanostructures in Optoelectronics and Photonics" (GRK 1464) is a preeminent example of the joint and coordinated research and of the commitment to teach and support young academics in this field.

It is a great honor that the research results of optoelectronics and photonics can be presented in this CeOPP brochure to the public today.

Prof. Dr. Nikolaus Risch, President of the University of Paderborn

October 2011



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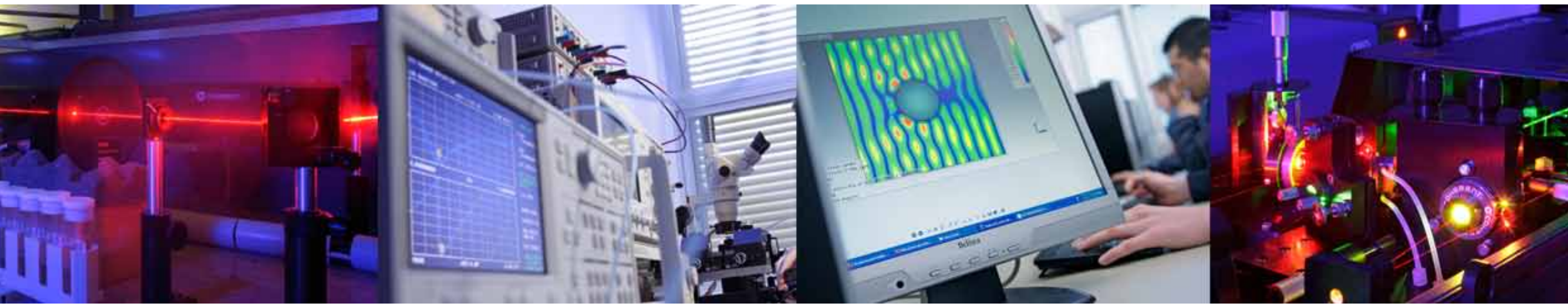


About CeOPP

Since 1989 the University of Paderborn is constantly promoting research and development in the fields of modern optical technologies. Over the years, this topical focus within our University was continuously developed into the fields of optoelectronics, photonics, and integrated optics, in accordance with the mission statement of the University of Paderborn as "University of the Information Society". An important prerequisite for this concept was the formation of an interdisciplinary group of designated researchers from the departments of physics, electrical engineering and information technology, and chemistry. Already in 1997 the Deutsche Forschungsgemeinschaft (DFG) started to support the activities in Paderborn with the establishment of the coordinated research unit "Integrated Optics in Lithium Niobate". In the year 2006, the central research facility "Center for Optoelectronics and Photonics Paderborn" (CeOPP) was founded on the basis of initially ten designated research groups. In the same year, the new building for optoelectronics, integrated optics, and photonics became available for the CeOPP researchers. Excellent clean room facilities, as well as top quality lab and office space can since then be used for corporate research and development. The jointly used clean room lab space provides an ideal seed for interdisciplinary research projects. We are therefore very pleased that 2008 marks the starting point of our new joint research activities on "Micro- and Nanostructures in Optoelectronics and Photonics" within the framework of the recently established DFG Research Training Group GRK 1464.

For teaching and education, the interdisciplinary structure of the CeOPP offers unique opportunities for Bachelor-, Master-, and PhD-students to acquire a broad and profound knowledge in optoelectronics and photonics, which are regarded as the enabling technologies of the next century. No matter whether the individual interests are oriented towards fundamental or applied aspects, towards theory, experiment, or technology, the appropriate lecture or internship is readily found in the Bachelor and Master programs of our departments. The mission of the CeOPP to promote the best possible professional qualification for the students is supplemented by the organisation of graduate lectures about hot topics in the field, presented by distinguished external speakers.

By now, 15 designated research groups are member of the CeOPP. Together they cover important areas of the innovative optical technologies of today, as presented to you in this brochure.

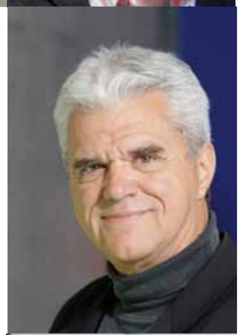
Prof. Dr. Artur Zrenner, Chairman of CeOPP

October 2011



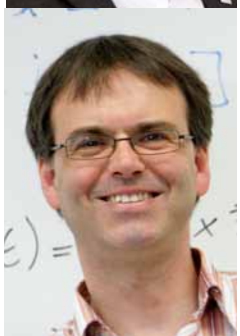



CeOPP Board




Faculty

- Prof. Dr. D. J. As - Experimental Physics
- Prof. Dr. S. Greulich-Weber - Experimental Physics
- Prof. Dr.-Ing. U. Hilleringmann - Electrical Engineering
- Prof. Dr. K. Huber - Chemistry
- Prof. Dr. H.-S. Kitzerow - Chemistry
- Prof. Dr. J. Lindner - Experimental Physics
- Prof. Dr. K. Lischka - Experimental Physics
- Prof. Dr. C. Meier - Experimental Physics
- Prof. Dr. T. Meier - Theoretical Physics
- Prof. Dr.-Ing. R. Noé - Electrical Engineering
- Jun.-Prof. Dr. S. Schumacher - Theoretical Physics
- Prof. Dr. C. Silberhorn - Applied Physics
- Prof. Dr.-Ing. A. Thiede - Electrical Engineering
- Prof. Dr. T. Zentgraf - Applied Physics
- Prof. Dr. A. Zrenner - Experimental Physics



Staff

- Torsten Frers
- Irmgard Zimmermann

Student Representative

- Sandro Hoffmann


Excellence in Integrated Quantum Optics: DFG Leibniz Prize for Prof. Christine Silberhorn

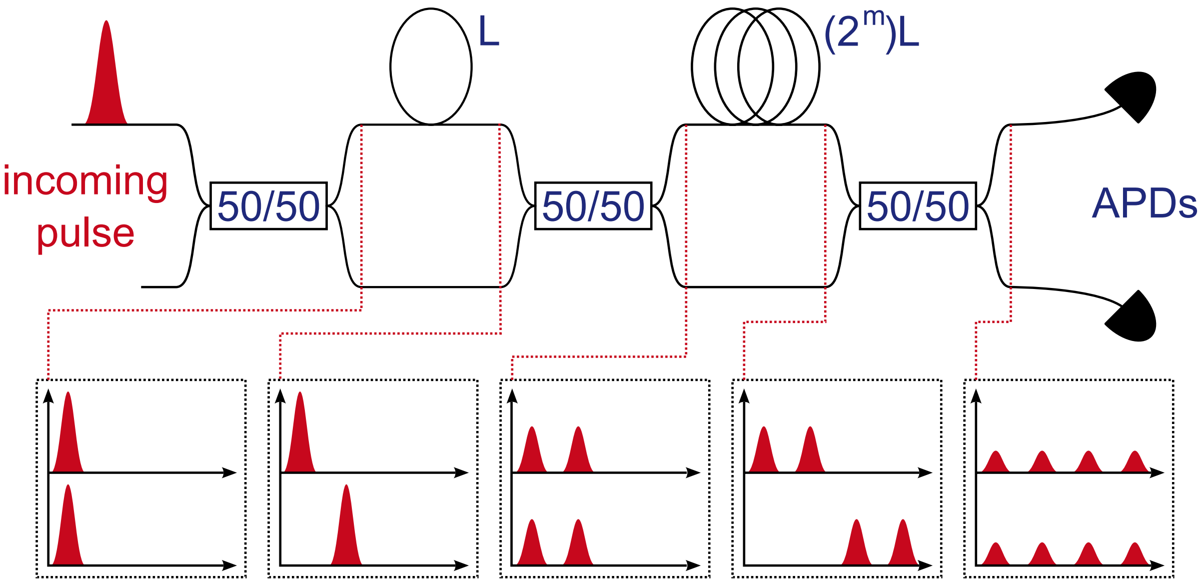
The quantum nature of light is today as fascinating as it was in 1900, when Max Planck showed that thermal radiation can be understood by emission and absorption of individual portions of energy-the discovery of the photon. Since then, many scientists have contributed to our fundamental understanding of the intriguing nature of light, which might be viewed as a particle as well as a wave, depending on the experiment. Today, applications of such quantum phenomena have come to the focus of research: Quantum computing and quantum cryptography are only two examples for a rapidly developing field of applications. For her innovative contributions in merging the fields of integrated optics and quantum optics, Prof. Silberhorn has been awarded one of the 2011 Leibniz Prizes by the Deutsche Forschungsgemeinschaft (DFG).

Modern electronic circuits driving computers rely mostly on large scale integration of active electronic components. Transistors and other devices are all fabricated on a single piece of silicon, thus allowing ultrafast clock rates up to the GHz regime. The development of this technology has contributed strongly to our everyday lives.

Stimulated by the success of integrated electronics, it is the idea of integrated optics to combine photonic components on a single chip by the use of microstructure technology. This way, one can benefit from the large bandwidth of photonic circuits as compared to electronic circuits. The use of nonlinear materials, such as the Lithiumniobate ($LiNbO_3$) and the Potassiumtitanylphosphate (KTP) used in Prof. Silberhorn's group, enables fascinating processes such as parametric downconversion, photon pair generation and all-optical switching of light.

In Prof. Silberhorn's group, the technology of integrated optical components meets quantum optics. This combination offers exciting possibilities for the development of compact devices that can serve as building blocks in integrated quantum optical systems.

For her research in quantum optics, Prof. Silberhorn also makes use of continuous variables instead of discrete variables. This has enabled her to realize Einstein-Podolsky-



Experimental setup for photon statistics measurement.

Photo: DFG/Ausserhofer

Prof. Dr. Christine Silberhorn, Prof. Dr. Matthias Kleiner.

Rosen (EPR) states inside an optical fiber by exploiting its nonlinear optical properties. Other important contributions are the development of fiber-based techniques for the experimental determination of photon number states. Such states are highly relevant for secure quantum information processing as well as for several linear optical quantum computing schemes.

The Gottfried-Wilhelm-Leibniz Prize of the Deutsche Forschungsgemeinschaft (DFG) is doped with a research grant of 2.5 million Euro. It is among the international awards for fostering research one of the most prestigious.

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Research Training Group Micro- and Nanostructures in Optoelectronics and Photonics

In April 2008, the University of Paderborn started a Research Training Group in the field of Optoelectronics and Photonics. It aims to offer an appropriate environment for preparing an excellent doctoral thesis within three years. In a very competitive international application procedure, the best candidates are elected. They benefit from a specific study program, an ambitious collaborative research program, state-of-the-art research equipment, advice from two supervisors, travel grants and international contacts through visiting scientists and invited seminar speakers. In addition, thirteen doctoral students and two postdocs receive a scholarship or hold a position. The program is funded as a "Research Training Group" by the German Research Foundation (DFG, GRK 1464).

Interdisciplinary Research

The interdisciplinary research program is focused on the fabrication, characterization and application of micro- and nanostructures. It covers such modern research topics as addressable photonic crystals and metamaterials, integrated optical structures based on lithium niobate, single-photon and entangled-photon light sources for cryptography, integrated lasers based on microresonators with built-in quantum dot emitters, and optical amplifiers based on erbium-doped microresonators. The materials range from polymers, liquid crystals and colloidal crystals (soft matter) to solid state semiconductors. Novel methods of computer simulation serve to calculate the electromagnetic wave propagation and nonlinear optical properties of complex nanostructures.

Research Program, Part A

Many projects of this interdisciplinary research require a close collaboration between experimentalists and theorists. Part A is focused on artificial structures with fundamentally new optical properties (photonic crystals and metamaterials), and integrated optical structures based on periodically poled lithium niobate (PPLN).

A. Periodic Structures

A1. Periodic silicon carbide-nanostructures for photonic applications (Greulich-Weber, Rauls)

A2. Self-organized binary colloidal mixtures (Huber, Greulich-Weber)

A3. Polymer-dispersed liquid crystals: Holography and confinement effects (Kitzerow, Schmidt)

A4. Switchable waveguides made of photonic crystal fibers and liquid crystals (Kitzerow, Schuhmann)

A5. Ferromagnetic composites, materials with negative refraction (Greulich-Weber, Schuhmann)

A6. „Orientation-patterned“ epitaxially grown Gallium nitride-waveguides on PPLN (Lischka, Sohler)

A7. Generation of entangled photon pairs in PPLN waveguides (Sohler, Zrenner)

AT. Electromagnetic field simulation; light-matter interaction in periodic structures (Schuhmann, Meier)

Research Program, Part B

Microresonators, i. e., small cavities that can trap light, are investigated in the second part of the research program. They may serve to direct light of specific frequencies or to enhance the emission of inorganic and organic semiconductor structures, eventually even enabling laser emission of structures that can be integrated in an optical chip.

B. Microresonators

B1. Single photon sources based on group III-nitrides (As, Lischka, Zrenner, Meier)

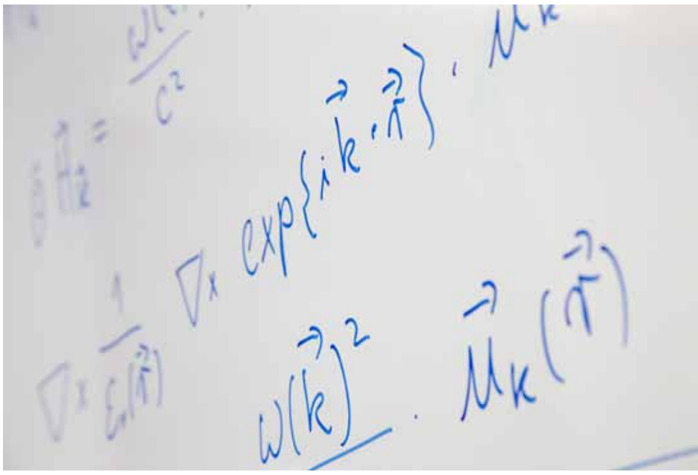
B2. Quantum dot emitters in planar photonic resonators (Zrenner, Förstner, Meier)

B3. Waveguide-coupled Erbium-doped SiO_xN_y-micro resonators (Hilleringmann, Zrenner)

B4. Micro resonator enhanced organic light emitting diodes (Hilleringmann, Kitzerow)

BT. Optical properties of semiconductor nanostructures: combination of ab-initio theory and Bloch equations (Meier, Rauls, Förstner)

Study Program



The specific training of the PhD students participating in the graduate program includes practical training courses, two lecture series about the fundamentals of the research subject, a series of seminars given by external speakers, practical skill training and a large choice of optional courses in science, engineering, languages etc. Once a year, the participants organize an internal scientific meeting, eventually together with an external research training group that works on a similar subject.

Lecture Series

"Fundamentals of Micro- and Nanostructures in Optoelectronics and Photonics"

Term	**Lecture Series I:** Fabrication and characterization of micro- and nanostructures	**Lecture Series II:** Structure-induced phenomena and their application
1	Semiconductor technology and modern nanostructuring (Hilleringmann)	Integrated optics (Sohler)
2	Colloidal crystals for photonics, liquid crystals, and photonic crystals (Greulich-Weber, Huber, Kitzerow, Schmidt)	Optical communications and optical micro sensors (Hilleringmann)
3	Computational electrodynamics, meta-materials (Schuhmann, Förstner, Meier)	Quantum structures and microcavities (As, Lischka)
4	Microscopy, spectroscopy and nano-optics (Sohler, Zrenner, Kitzerow)	Microscopic modeling and quantum optics (Rauls, Förstner, Meier)

PACE

The Paderborn Institute of Advanced Studies in Computer Science and Engineering (PACE), a central unit of the university, supports the graduate program by administrational services, international advertising, organizing practical skill training courses and cultural events. Among the most welcome PACE activities are an annual celebration of all participants of graduate programs in science and engineering in Paderborn and an annual soccer contest.

Qualifying Studies

Excellent students have the opportunity to participate in extensive studies that qualify for starting their doctoral research one year after having received the Bachelor degree.

Applications

International applications for admittance to the graduate program are very welcome. Terms, dates and an application form can be found on the internet (www.ceopp.de/grk).

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Group III-nitrides for optoelectronics

Prof. Dr. D. J. As

Group III-Nitride forms a new class of semiconductors for modern applications in optoelectronics and electronics. They form the basis for the well known white light emitting diodes (LEDs) for energy saving future lightings and offer the way to fabricate blue and UV-lasers for gas spectroscopy or water purifications. Due to the large band offsets between the different semiconductors within these group III nitrides (AlN, GaN and InN), novel nitride devices based on quantum mechanical effects like intersubband transitions (ISBT) are suggested. New quantum well infrared photodetectors (QWIPs) or Quantum Cascade Lasers (QCL) operating at the telecommunication wavelength of 1.55 µm are proposed. Besides applications in optoelectronics, the high thermal stability and it´s inertness against harsh ambience predestine group III nitrides also to be employed in electronics for novel high-power, high-frequency devices (e.g. field effect transistors).

The main research fields of the group, headed by apl. Prof. Dr. Donat J. As, is the growth, characterization and development of optoelectronic and electronic devices. A molecular beam epitaxy (MBE) system is used to grow the group III-nitrides (Ga, In, Al) N with cubic crystal structure and first low dimensional micro- and nanostructures devices are produced.

MBE growth of cubic Nitrides

Commercially available group III-nitrides have a hexagonal crystal symmetry, which leads to strong "built-in" piezoelectric and spontaneous polarization fields, which may limit the performance of devices containing quantum wells or may prevent the realization of field-effect transistors with enhancement characteristics. Polarization fields are absent in (100) oriented cubic III-nitrides.

We grow phase-pure cubic III-nitride epilayers and quantum wells (QW) by molecular beam epitaxy (MBE) and have demonstrated first 1.55 µm inter-subband absorption in cubic AlN/GaN superlattices and the realization of cubic GaN/AlN quantum dots (QDs) for applications as single photon emitters.

Optoelectronic applications

Thanks to the recent advances in the material growth and fabrication technologies, GaN/AlN superlattices have become the system of choice for intersubband (ISB) devices operating at telecommunication wavelengths (1.55 µm), such as for example fast photodetectors or modulators. Recently it has been predicted that due to the large optical phonon energy in nitride-based semiconductors, these materials are very promising candidates for ISB lasers emitting in the Terahertz (THz) domain with room-temperature operation. The ISB absorptions in cubic GaN/AlN quantum wells (QWs) have been observed in the near infrared spectral range.

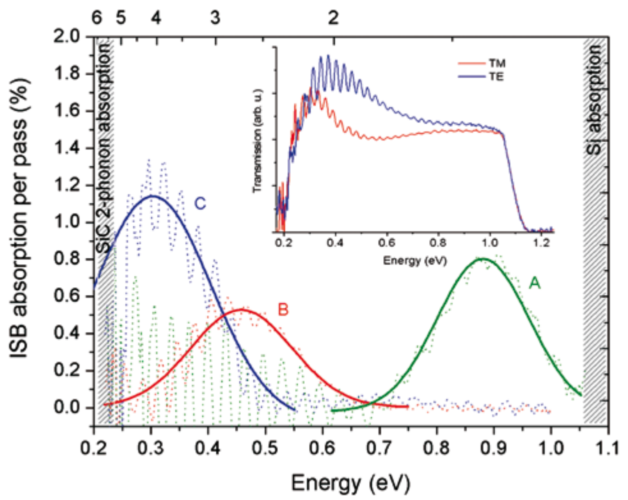

Fig. 1: Transmission spectrum in the THz range of the GaN/AlGaN cubic QWs at 4.2K for TM- (red solid line) and TE- (blue dotted line) polarized light. ISB absorption is peaked at 4.76 THz.

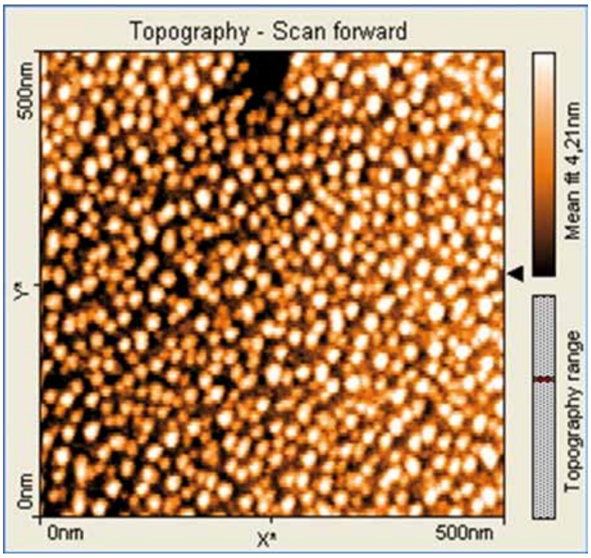

Fig. 2: Atomic Force Microscopy (AFM) image of cubic GaN quantum dots (QDs) on cubic AlN grown by Molecular Beam Epitaxy (MBE) with the Stranski-Krastanov method (area 0.5x0.5 µm², density 5x10¹¹ cm⁻²).

We show that by changing the QW thickness and Al content it is possible to tune the ISB absorption wavelength over a wide spectral range from 1.4 µm (214 THz) to 63 µm (4.76 THz). These values correspond to the shortest and the longest wavelengths for ISB transitions ever achieved in this material system.

Within the research graduate school cubic GaN based quantum dots (QDs) are fabricated and will be applied in single photon sources for the visible spectral range.

Electronic applications

AlGaN/GaN hetero-junction field-effect transistors (HFETs) are of major interest for use in electronic devices, in particular for high-power and high-frequency amplifiers. Currently, state of the art HFETs are fabricated of the c-plane surface of wurtzite (hexagonal) AlGaN/GaN heterostructures. Their inherent spontaneous and piezoelectric polarization fields produce extraordinary large sheet carrier concentrations at the AlGaN/GaN hetero-interface. Therefore, all these devices are of the normally-on type. However, for switching devices and digital electronics field-effect transistors (FET) with normally-off characteristics are desirable. Due to the absence of spontaneous and piezoelectric fields, cubic AlGaN/GaN provides an incentive for fabrication of heterojunction field-effect transistors with both normally-on and normally-off characteristics.

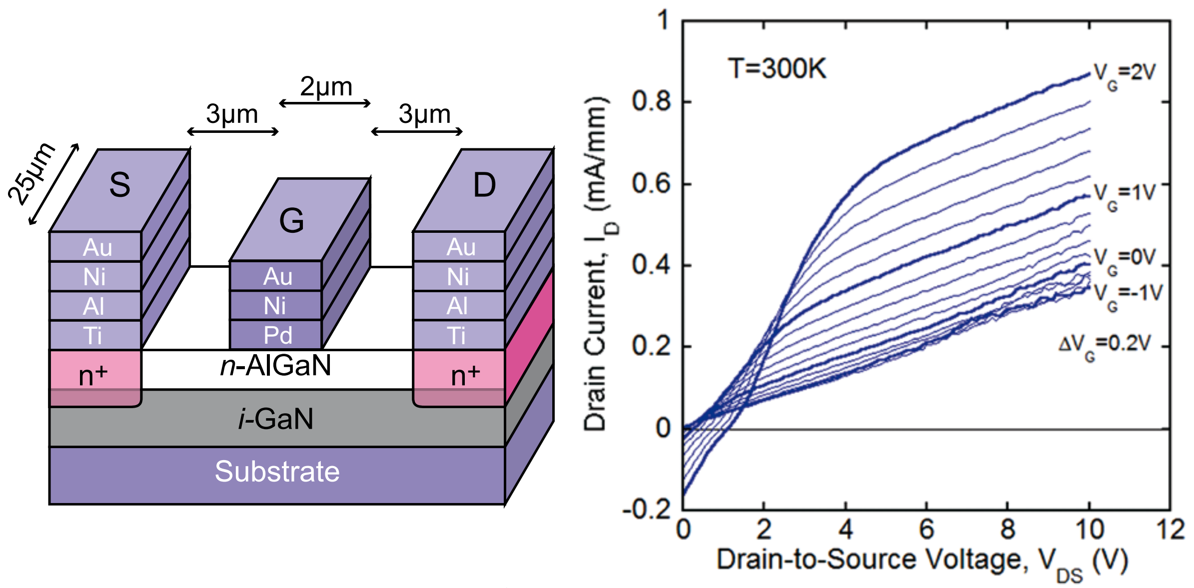

Fig. 3: Schematic drawing of a cubic GaN/AlGaN field effect transistor (left) and its output characteristics (right).

Group Members

- Prof. Dr. Donat J. As
- Thorsten Schupp
- Christian Mietze
- Alexander Zado
- Ricarda Maria Kemper
- Matthias Bürger
- Tobias Wecker

Equipment

- Riber 32 Molecular Beam Epitaxy for Nitrides
- High energy electron diffraction (RHEED)
- Quadrupol mass spectrometer (QMS)
- Metal Evaporation System
- UV - Photoluminescence (2-300K)
- Hall-Effect Apparatus (10-400 K)
- Electrical Parameter Analyzer
- Probe station for I-V and C-V
- Reflectometry

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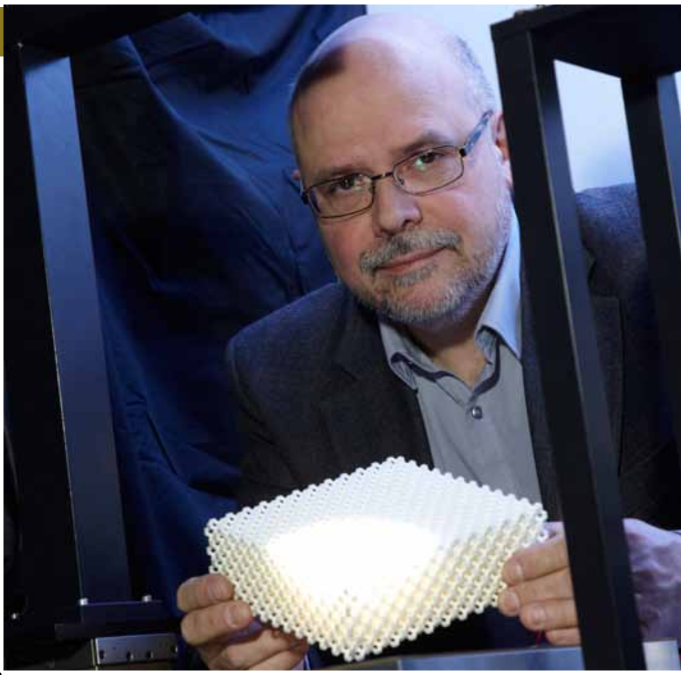
Hybrid Materials for Photonics

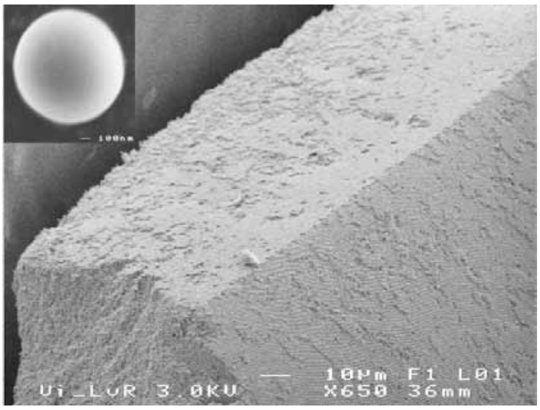
Prof. Dr. S. Greulich-Weber



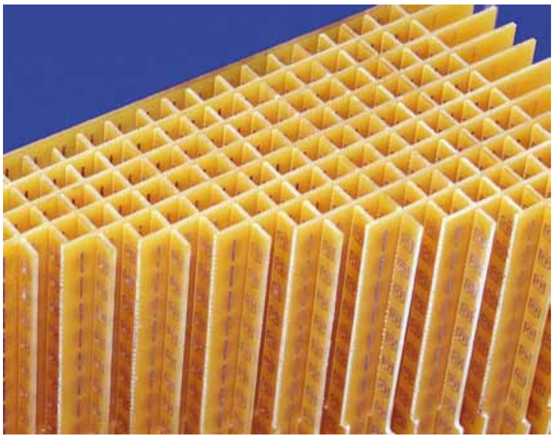
Hybrid materials are materials prepared by combining organic and inorganic materials designed on the micro- or nanoscale. The combination of such materials leads to new exciting functionality and effects with highly tailorable properties. For the fabrication of inorganic materials we use sol-gel-based processes. Our focus is currently on wide-band-gap semiconductors, such as silicon carbide (SiC), titanium dioxide (TiO_2) or zinc oxide (ZnO) which are very promising materials for numerous photonic applications. Various growth conditions lead to nano or micro crystals and fibers. Additionally, porous and bulk semiconductors are grown.

The development of new materials needs a deep understanding of the materials properties. Thus various kinds of spectroscopy are needed. Among common optical spectroscopy, our field of expertise is magnetic resonance spectroscopy with various techniques such as optically or electrically detected multiple resonance spectroscopy, allow the determination of the microscopic structure and chemical nature of defects in materials. The knowledge of defects in materials is important for a detailed understanding of electrical and optical properties of materials and thus allows the application of such defects for device application.

Photonic Crystals

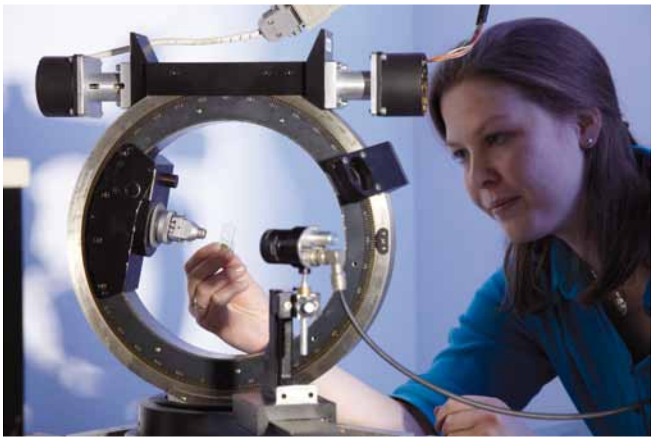


Photonic crystals are usually viewed as an optical analogue of semiconductors that modify the properties of light similarly to an 'atomic' lattice that creates a semiconductor band gap for electrons. Photonic crystals are periodic dielectric or metallo-dielectric structures in which the refractive index is periodic in one, two or three dimensions creating a bandgap at optical frequencies. The photonic bandgap gives rise to distinct optical phenomena such as suppression of spontaneous emission, low-loss waveguiding and high-reflecting omnidirectional mirrors among others. Our group has long lasting experience in growing photonic crystals as self-assembled structures from so-called colloidal crystals, which are artificial crystals, made of spheres with diameters less than a micrometer. Such sub-micron spheres are prepared by a sol-gel process of favoured materials like silicon carbide, zinc oxide, titanium dioxide, carbon and others. For the fabrication of massive photonic crystals a fully automated crystal growth was developed. In order to study the features of photonic crystals a custom-made optical Laue reflection spectrometer with energy resolution is used.

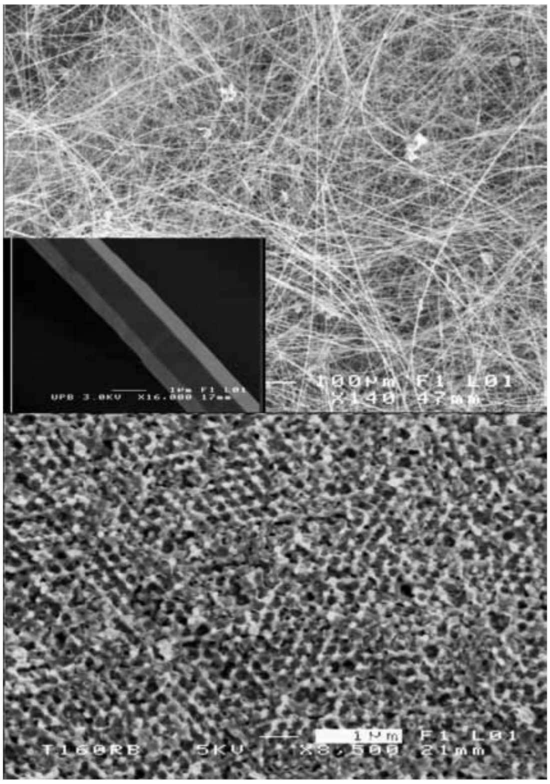


Metamaterials

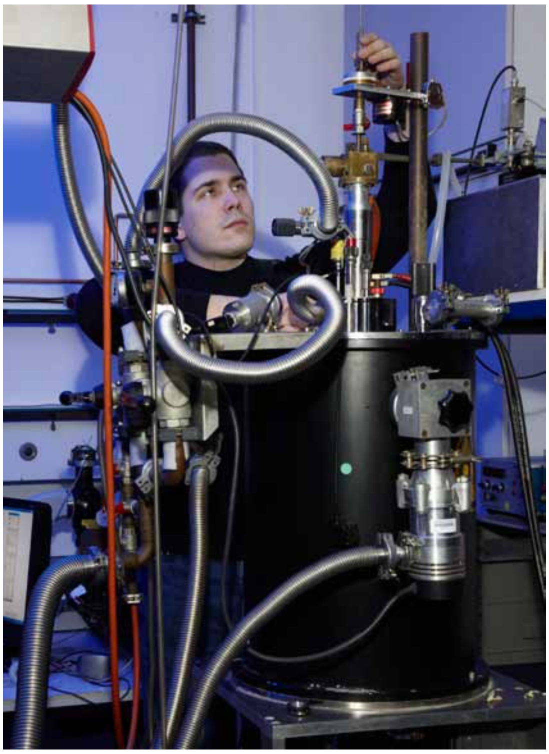
Metamaterials are artificial optical materials where the effective permeability (μ) and permittivity (ε) can be adjusted. Classical metamaterials have an adjustable positive μ and ε. They consist, e.g., of coils and inductors far away from their resonance. However, close to the resonance of artificial coils and inductors, their μ as well as their ε can be negative. If only one of both is negative, there is no propagation allowed. If however, both are negative, propagation is allowed and a new class of left-handed materials with very peculiar properties can be obtained. Such materials were first realized in the microwave range, since the necessary elements are easily obtained by micro-structuring. Metamaterials with negative refraction are often thought to require ordered arrays of capacitors and inductors. However, metamaterials do not necessarily rely on interference, they are effective medium materials. Therefore, extension of metametarials to the THz or visible light range do not require necessarily high precision lithography, but could in principle been carried out by tailor-made nanocomposites.



Sol-gel-based semiconductors



The group has extensive experience in the development of sol-gel routes for the fabrication of wide-bandgap semiconductor materials. Among others silicon carbide (SiC), titanium dioxide (TiO_2) and zinc oxide (ZnO) are of main interest. Depending on the sol-gel annealing procedure one obtains macro-porous, amorphous, or from nano to micrometer-sized single crystals. At low annealing temperatures preferably nano- or microwires are grown. Not only for photonic applications practicable procedures for doping with shallow level donors and acceptors as well as with deep level defects were developed. Applications of varieties of sol-gel semiconductors are photonic crystals, photovoltaic elements, light emitting diodes, light weight structures, filters, sensors and many more, beneficial in combination with organic materials.



Magnetic resonance spectroscopy

Defects, even as contamination with extremely low concentration, may strongly determine the electrical and optical properties of materials. Thus, the knowledge of the chemical nature and their microscopic structure is important either to avoid them or to use them technologically. A powerful tool for the investigation of defects in materials is magnetic resonance spectroscopy. We have long lasting experience with these methods, in particular with electron paramagnetic resonance and electron nuclear double resonance either conventionally, electrically or optically detected.

Group Members

- Thorsten Audersetz
- Tim Baumgarten
- Christoph Brodehl
- Frederico Dias Brandão
- Dennis Briese
- Diana Deneke
- Kamill Eliasch
- Vera Eikel
- Siegmund Greulich-Weber
- André Konopka
- Lisa von Rhein
- Frank Schnaase
- Syed Jahanzeb Azam
- Andreas Scholle
- Benjamin Thiele
- Mark Zöller

Equipment

- Sol-gel reactors
- High temperature furnaces
- Magnetic resonance spectrometers (optically and electrically detected electron paramagnetic resonance and multiple resonance)
- Free-space microwave near-field scanner
- Energy-resolved 3d optical reflection spectrometer
- PV test site

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Sensor Technology

Prof. Dr. Ulrich Hilleringmann

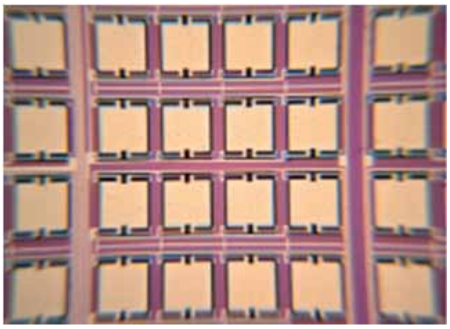
The Sensor Technology group at the University of Paderborn, Faculty of Computer Science, Electrical Engineering and Mathematics, has been founded in 1999. The research work focuses on micro- and nanometer scale integrated sensors applying modern semiconductor processing and sensors for process automation.

In the area of automation technology new sensors or process applications are developed, e. g., passive RFID tags and readers with electronic ink displays, particle counters based on piezoelectric sensors, and algorithms for active noise control in tubes.

The actual research emphasizes flexible field effect transistors, electrostatic and electrothermal micromechanic actuators for micromirrors, surface acoustic wave sensors (SAW) to specify the quality of liquids in automotive applications, and integrated gas sensors for hydrogen and carbon oxide.

Micro Mechanics

Silicon bulk micromechanics has been applied for the integration of tiltable micromirrors. The mirrors consist of thin silicon membranes which are fixed by silicon cantilevers at four points. The cantilevers are covered by a titanium resistor on top as a heating element. So the cantilevers serve as thermal actuators using the bimetal effect. The mirrors can be tilted in two perpendicular directions for several degrees. Power dissipation for a single mirror is about 100 mW at a tilt angle of about 5 degree, which is large compared to electrostatic actuation.

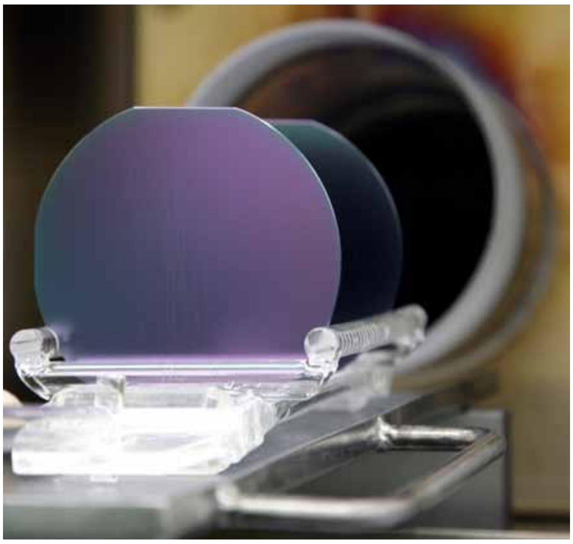


Micro mirror array for optical applications.

Surface micromechanics use components consisting of polycrystalline silicon films. An electrostatic motor has been integrated as an actuator for the movement of wheels and comb drives.

Organic Field Effect Transistors

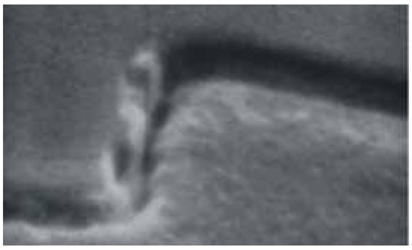
OFET are the basic elements for 'low cost – low performance' microelectronic circuits. The organic semiconducting material is cheap to produce and easy to handle, resulting in a cost-efficient integration of microstructured circuits. Using the technology of spin coating or thermal vacuum evaporation, the organic semiconductor can be easily deposited on rigid silicon wafers as well as on flexible polymer substrates. Basically, it is conceivable that the circuit integration will be carried out in a roll-to-roll printing process. With this, a large field of new applications opens up, e.g., electronic water marks, transponders, electronic barcodes, flexible smart cards, and integrated circuit drivers for sensors and actuators for single use medical applications.



The aromatic hydrocarbon pentacene is one of the most promising small molecules. Until today, the main problems are a high contact potential, a rapid degradation as well as low charge carrier field-effect mobility. Our aim is to reduce the operating voltage in adjusting the work function of the contact metals and using high dielectric constant insulation layers. With these technological solutions, charge carrier mobilities of 0.5 cm^2/Vs have been achieved. Degradation experiments revealed a strong influence of ambient air on the threshold voltage, the mobility, and the maximum on-current of the OFET. Nevertheless, the devices were found to be still operating after a period of 9 month under ambient air conditions. Future investigations will be carried out to quantify the influence of the humidity of ambient air.

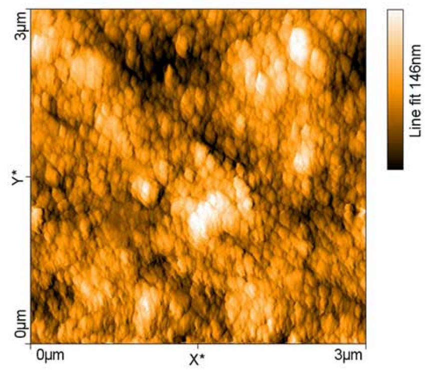
Nanometer Scale Technology

The excellent uniformity of layer deposition and layer etching in silicon technology is applied to form nanometer scale lateral structures on top of silicon wafers using optical lithography only. Minimum feature sizes of 30 nm with a standard deviation of about +/- 5% have been demonstrated on a 100 mm wafer. The technique has been used to etch polysilicon gates for MOS transistors, aluminium metal wires, silicon oxide and nitride lines.



SEM micrograph of an 80nm trench.

Special processing techniques enable the integration of nanometer scale trenches in metal layers. The trenches were filled with semiconducting nanoparticles (Si, ZnO) to form field effect transistors. Semiconducting nanoparticles for transistor purposes provide several advantages due to their superior degradation behaviour, carrier mobilities, and supply voltages, while covering all applications of organic electronics. Key features of this innovative technology are the exceedingly reduced costs for semiconducting material in combination with a wide variety of substrates, e.g., plastic foils.



AFM-topography of a silicon nanoparticle surface.

In the first state of research, transistor devices have been integrated on standard silicon substrates. Using metals for all electrodes and silicon-related materials for the dielectrics, carrier mobilities of 0.2 cm^2/Vs and 0.05 cm^2/Vs have been achieved for Si- and ZnO-nanoparticles, respectively. Further research is focused on the most challenging issues of process stability, contact potential engineering and the transition to glass and foil substrates employing nanotechnology composite materials.

Group Members

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- Werner Büttner
- Torsten Frers
- Christian Hangmann
- Wiebke Hartmann
- Thomas Hett
- Prof. Dr. Ulrich Hilleringmann
- Sandro Juca
- André Kleine
- Michael Knüpfer
- Thomas Markwica
- Sebastian Meyer zu Hoberge
- Benjamin Ohms
- Dmitry Petrov
- Sabine Schleghuber
- Marcel Schönhoff

Equipment

- Lithography (0.8µm)
- Dry Etching (RIE, ICP, PE)
- LPCVD (SiO_2, Si_3N_4, Poly-Si)
- PECVD
- Sputtering/Evaporation
- Oxidation/Diffusion
- Parameter/Network Analyzer
- Wafer Prober

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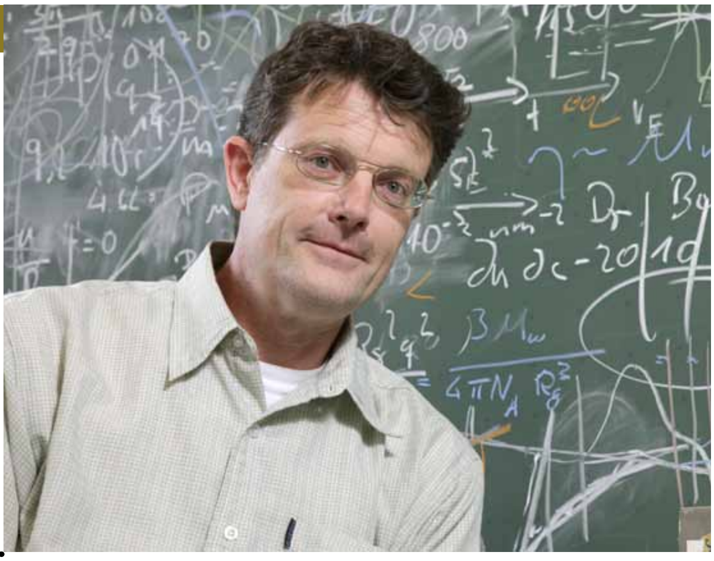
Soft Matter

Prof. Dr. K. Huber



A common feature of all our research activities is to unravel mechanisms of structure formation in nature, both intra-molecular and supramolecular. Final objective is the development of tools to control these processes. Four related topics can be distinguished:

1. **Conformational changes of polyelectrolyte chains induced with specifically interacting metal cations**
2. **Nucleation and growth of inorganic particles**
3. **Organization in complex colloid suspensions**
4. **Self assembly of low molecular weight gelators and biopolymers**

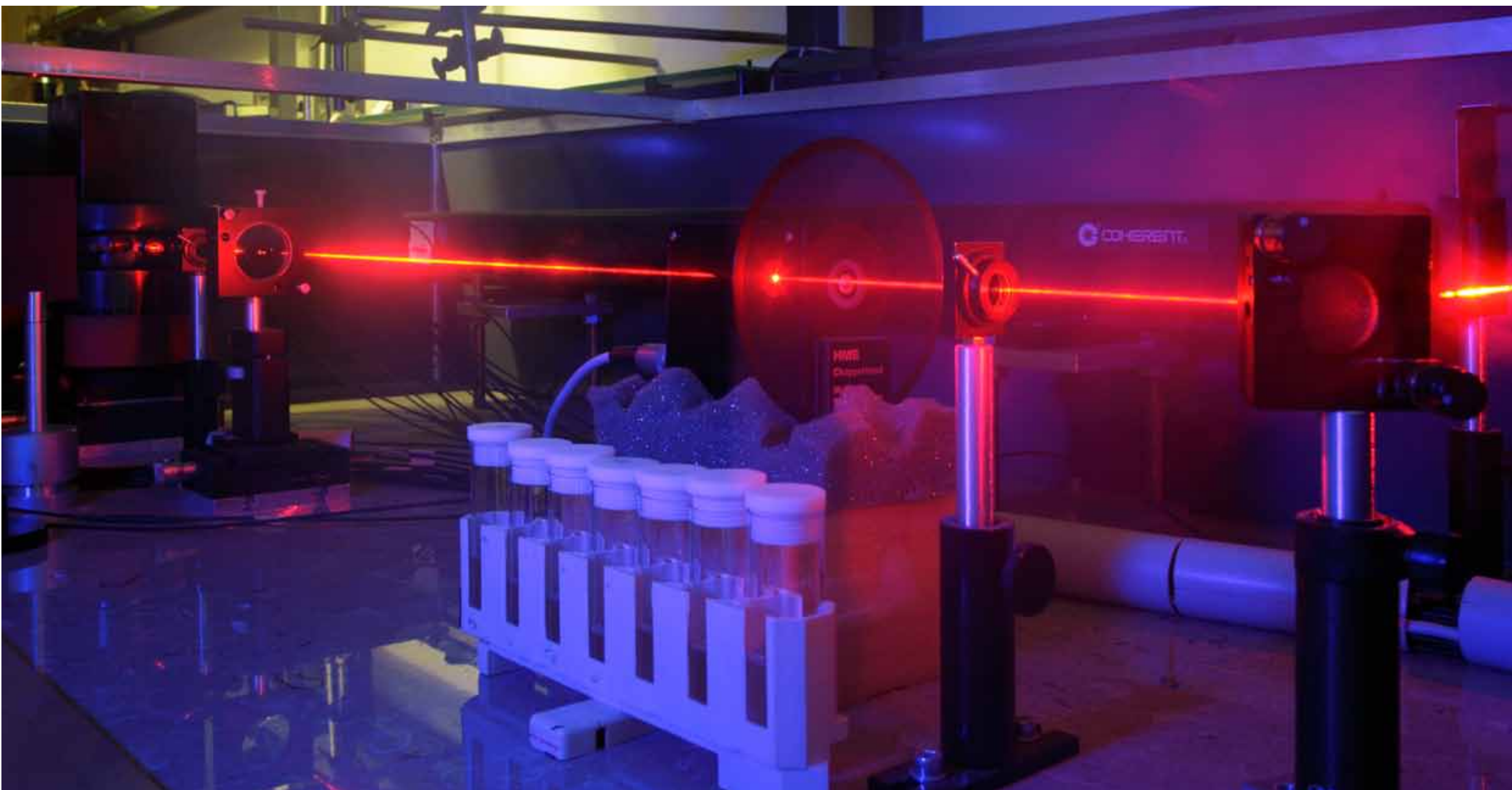
State of the art light scattering (LS), time-resolved static LS, small angle neutron scattering (SANS) and small angle X-ray scattering (SAXS) are predominantly used to gain insight into the mechanisms of these structural transformations.

Conformational changes of polyelectrolyte chains induced with specifically interacting metal cations

Polymer chains with electric charges along the chain backbones act extremely sensitive towards the addition of inorganic salts and changes of pH and temperature. This is reflected in a drastic change of the polyelectrolyte coil dimension and eventually in a precipitation, once the metal ion content is large enough. It is this sensitivity which makes them ideal candidates for responsive materials. Our main focus lays on specific interactions of alkaline earth cations or transition metal cations like Ag^{+} or Pb^{2+} with the carboxylate residues of anionic polyacrylate chains. We could show that metal induced precipitation in this case is preceded by a dramatic coil shrinking to compact spheres. The subtle interplay of an added inert salt with appropriate amounts of specifically interacting cations enabled us to select any intermediate state along this shrinking process by combined static and dynamic LS and to look for structural details of such intermediates by SANS (at the D11, ILL in Grenoble) and anomalous SAXS (at the JUSIFA, DESY in Hamburg). Whereas SANS and LS yield information on the size and shape of the polyanion, anomalous SAXS gives insight into the distribution of bivalent counterions like Sr^{2+}-ions. A combination of these techniques revealed pearl necklace-like intermediates before reaching the shape of compact spheres.

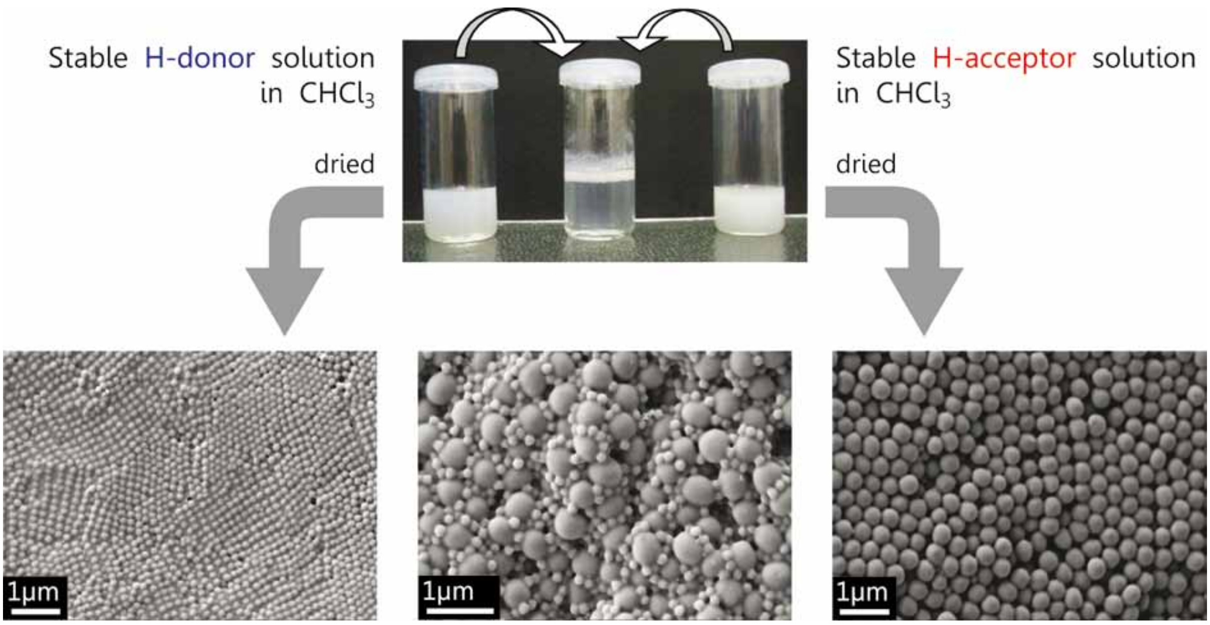
Nucleation and growth of inorganic particles

Nucleation and growth of particles are essential features of the formation of stable and metastable solid phases. These processes are of fundamental importance, bearing considerable relevance to numerous processes in nature and industry. Typical examples are the formation of high performance materials from supersaturated solution of calcium carbonates and phosphates in nature or the development of highly porous materials like metal organic frameworks (MOF) in order to store hydrogen or catalysts. We established a procedure to investigate the formation of amorphous $CaCO_3$ (ACC) with time resolved static light scattering (TR-SLS). This procedure is based on an in-situ formation of carbonate anions or on the appropriate mixing of components. The results were supplemented by SAXS experiments at the ESRF in Grenoble and provided new insight into the mechanism of particle formation and the morphology of these particles. Aside from ACC we currently start to investigate the formation of MOF particles based on ZnO and 1,4-benzenedicarboxylate.



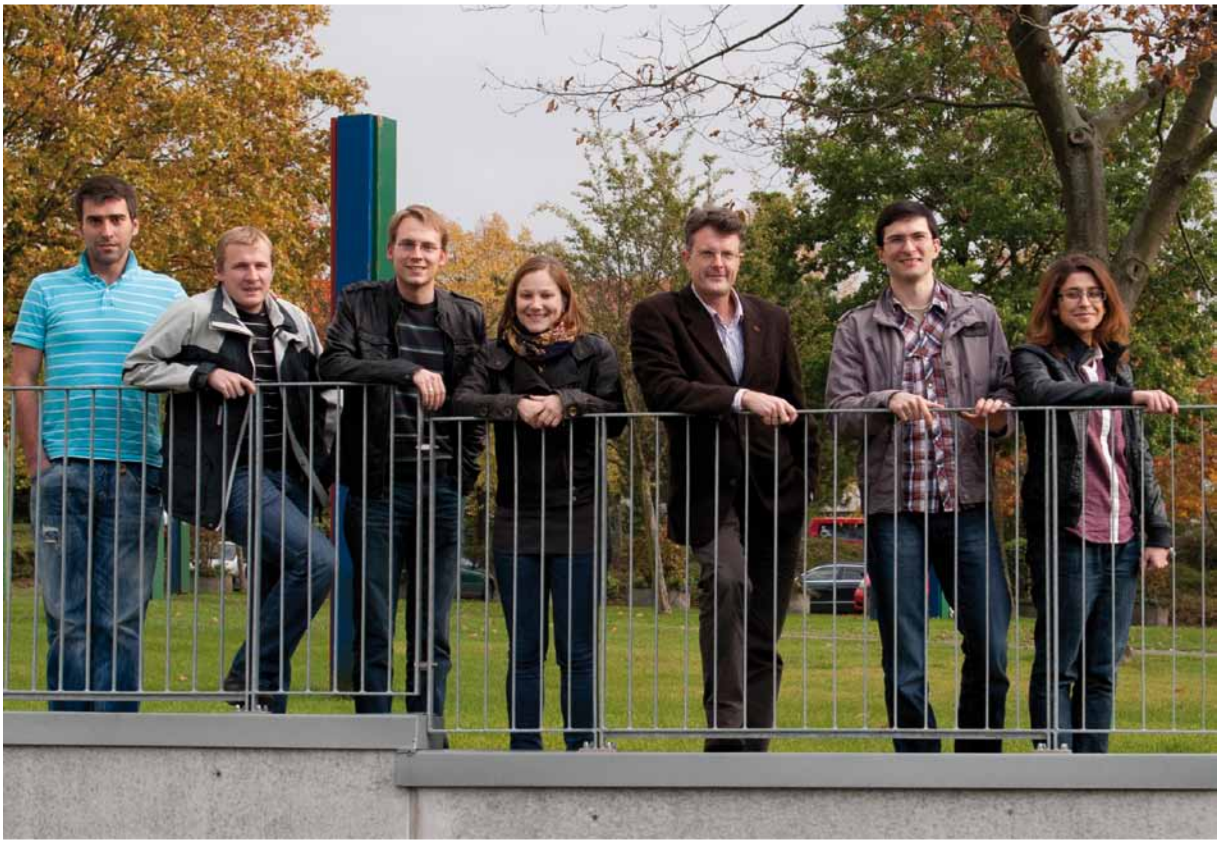
Organization in complex colloid suspensions

Spherical colloids exhibit striking analogies to atoms and to small proteins. Unlike to atoms, interaction potentials of colloids can be modified by means of chemical surface modification or with the help of additives. This makes them a highly interesting class of compounds, ready to be used to investigate interaction patterns of proteins or to tune organization of colloids into highly ordered assemblies. A prominent example is the introduction of an attractive potential among the colloids by means of non-adsorbing polymer coils. We currently focus on the design of new colloidal systems capable of forming crystal-like assemblies suitable for photonic band gap materials. This aim is pursued by means of the following strategy. First, monodisperse colloids with variable size and complementary surface coverage are prepared. A suitable surface coverage is the chemical modification of the colloids with either H-bond acceptors or donors respectively. Subsequently, binary mixtures of these complementary colloids shall be generated and techniques be developed, which lead to binary crystals with an NaCl-like lattice to give but an example. Such crystals are expected to show band gaps differing from the ones of simple fcc or bcc lattices.



Self assambly of synthetic gelators and biopolymers

Numerous synthetic, low molecular weight compounds form aggregates in solution in close analogy to fiber forming proteins in living cells. The underlying process can be regarded as a physical polymerisation with a structural diversity which is just as large as the complexity observed in macromolecular chemistry. In order to reveal general principles on this self assembly, several low molecular weight systems were selected for a detailed investigation with time resolved LS. These systems comprise Aβ-amyloid responsible for the Alzheimer’s disease as well as water solvable azo-dyestuffs or and 3,4,5-tris(octyl)benzamide in organic solvents like toluene. It is the final goal to develop tools to control aggregate size, size distribution and aggregate morphology.



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- Dr. Todor Hikov
- Prof. Dr. Klaus Huber
- Rolf Michels
- Roman Nayuk
- Martin Schneider

Equipment

- ALV 5000E CGS for static and dynamic light scattering (LS)
- Home built static LS instrument for time resolved experiments
- High temperature GPC Alliance 2000
- Differential refractometers

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Liquid Crystals

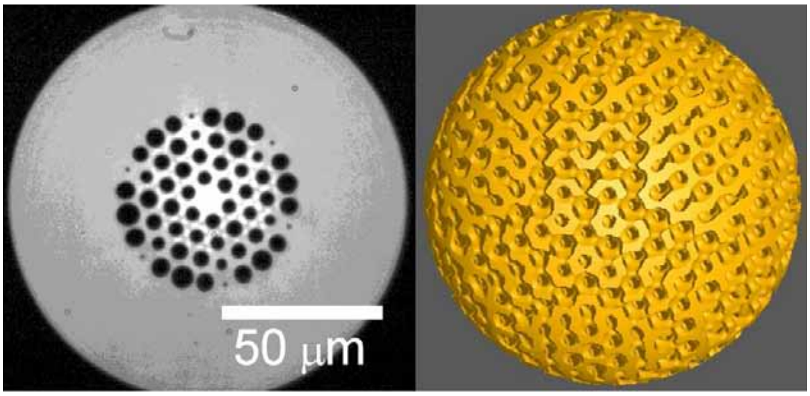
Prof. Dr. H.-S. Kitzerow

Liquid crystals are ordered fluids that play an important role in living organisms and in information technology. Flat TV and computer screens make use of thermotropic calamitic liquid crystals, which consist of rod-like molecules that are preferentially parallel aligned. This orientational order leads to birefringence, an optical phenomenon well known from solid crystals. In liquid crystals, however, the difference between the principal refractive indices is very sensitive to temperature changes. In addition, the orientation of the optical axis can be controlled by external electric or magnetic fields. This optical sensitivity can not only be applied for displaying images, but is also very promising for the development of novel active photonic devices that are based, for example, on tunable photonic crystals or diffractive optical elements with variable diffraction efficiency. Orientational order may also cause enhanced charge carrier mobility or give rise to polarized luminescence, which can be used for polarized light sources. Modern nanofabrication tools will certainly promote emerging liquid crystal technologies. Consequently, our work is focused on micro- and nano structures functionalized by means of liquid crystals.

Tunable Photonic Structures

During the last few years, the group has extensively worked on photonic crystals, periodic structures with lattice constants in the micrometer and sub-micrometer range. Natural structures of this kind cause the iridescent colors of minerals (such as opal) or animals (for example, peacock or butterflies). But the corresponding diffraction phenomena can also be used in photonics in order to enhance the emission or absorption of light, to fabricate optical waveguides or to control the color, the intensity or propagation direction of light. Through the infiltration with liquid crystals, the unique optical properties of photonic crystals become tunable and can be controlled by temperature or external fields. In addition, the helical structure of cholesteric liquid crystals can be applied for tunable DFB lasing.

Defects in photonic crystals and semiconductor microdisks may serve as high-quality microresonators, which emit light with an extremely narrow linewidth (see Prof. C. Meier's contribution in this brochure). The opportunity to control their emission frequency by means of liquid crystals is likely to enable the development of novel integrated light sources for IT or analytical applications.



Cross-section of a photonic crystal fiber (to the left) and three-dimensional structure of a holographic polymer-dispersed liquid crystal.

In order to explore the opportunities of liquid crystal infiltration for fiber optics, we study the transmission spectra, polarization properties and electrooptic switching behavior of microstructured fibers. The latter are fabricated at the Institute of Photonic Technologies (IPHT), Jena, and theoretically analyzed in collaboration with Prof. Rolf Schuhmann (TU Berlin).

Organic Optoelectronics

Liquid crystalline order can also enhance the charge carrier mobility, which plays an essential role in organic electronics. Thus, very thin layers of liquid crystals can be applied for organic light emitting diodes or photovoltaic cells. Linearly polarized emission at high conversion efficiencies can be achieved by a uniform alignment of electroluminescent liquid crystal molecules. For this purpose, spin-coating or physical vapor deposition in high vacuum are used to deposit very thin organic layers on a transparent conducting substrate with a suitable alignment layer.

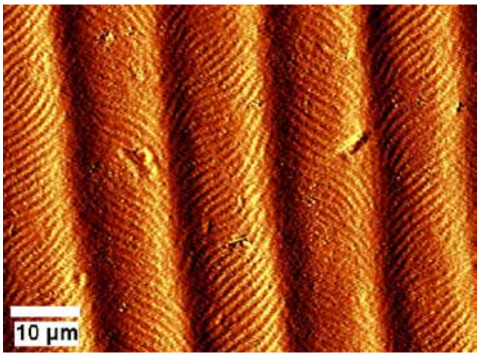
Luminescent liquid crystals and high vacuum chamber for fabricating thin electroluminescent layers.

Thanks to funding by the European Science Foundation, we explore the benefits of dispersed nanoparticles and mesogenic dendrimers on optoelectronic systems, such as heterojunction organic solar cells, together with researchers in York (GB), Warshaw (PL), Strasbourg (F), Neuchatel (CH) and Zaragoza (ES).

Liquid Crystal Composites

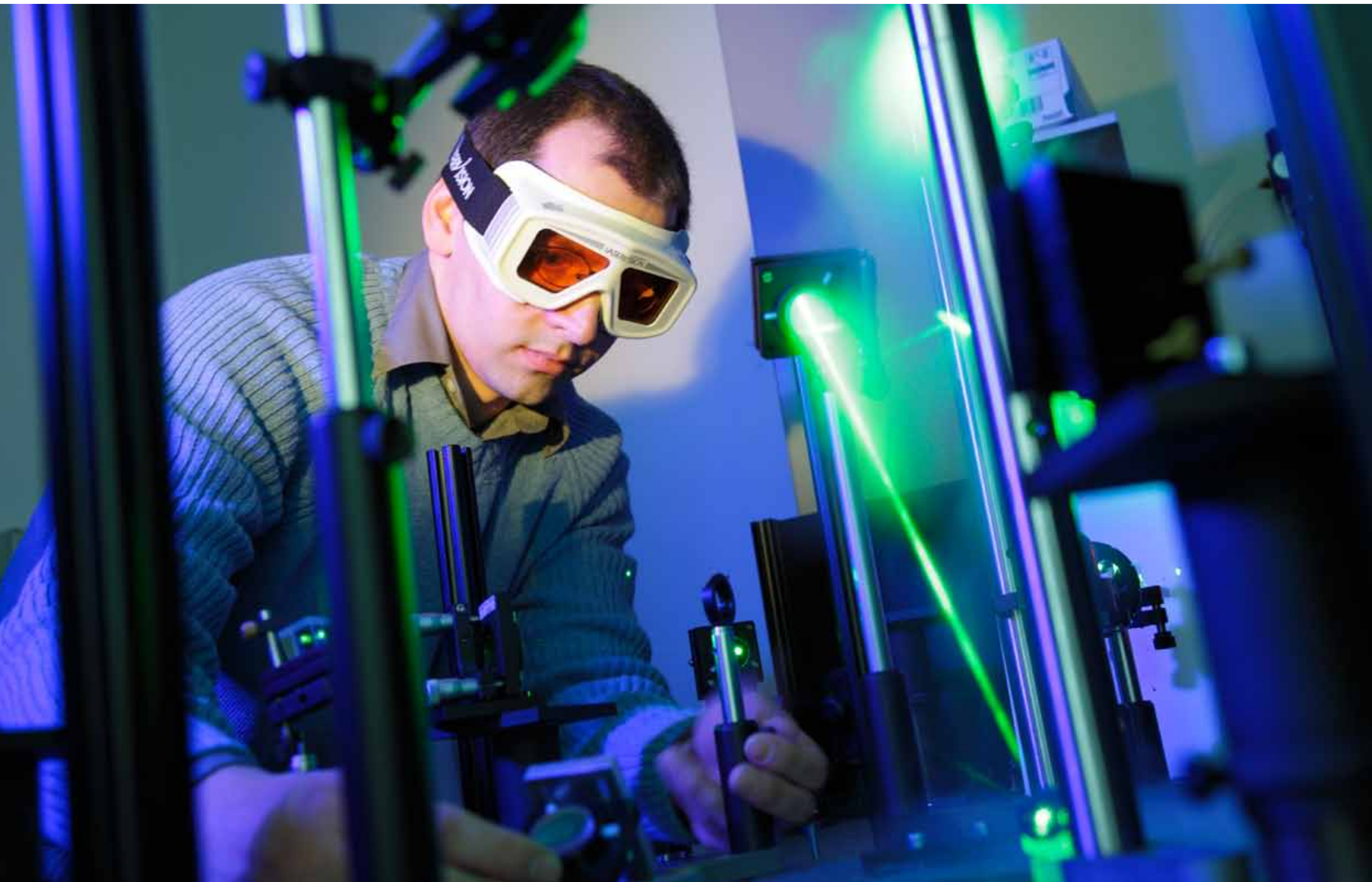
Combining the anisotropic optical properties of liquid crystals with the mechanical properties of polymers has a large potential for developments and applications beyond flat screens. Flexible displays, optical polarizing or compensating filters, switchable holograms and optical storage are just a few examples of emerging technologies.

During the last years, the liquid crystal group in Paderborn has explored the gray scale capability of gel-like ferroelectric and antiferroelectric liquid crystal composites, optical storage in photoreactive cholesteric liquid crystals, the formation and diffraction efficiency of holographic polymer-dispersed liquid crystals and the photorefractive effect in composites made of a photoconducting polymer and a liquid crystal.



But also dissipative structures caused by electroconvection can be utilized for fabricating regular microstructures: The figure to the left shows the surface shape of a polymer film (detected by atomic force microscopy), where a transient pattern induced by a uniform electric field was permanently imprinted into the polymer surface by means of photopolymerization. The lattice constant of the chevrons is smaller than 1 micrometer.

Recent activities include extensive investigations on dispersions of metal-, luminescent semiconductor- or ferroelectric nanocrystals. Confocal microscopy, X-ray diffraction and electro-optic studies indicate that nanoparticles can alter the alignment, the order parameter and the electro-optic switching behavior. The switching from a bright ground state to a field- induced dark state can even be inverted (dark ground state, field-induced bright state) by adding nanoparticles to a liquid crystal.



Group Members

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- Rita Egert-Tiesbohnenkamp
- Jonas Elsing
- Dr. Karl Hiltrop
- Dr. Andreas Hoischen
- Gisela Jünnemann
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- Dr. Jürgen Schmidtke
- Martin Urbanski
- Joachim Vollbrecht
- Markus Wahle
- Julia Weiß
- Natalie Zimmermann
- Sophie Zimmermann

Equipment/Methods

- Synthesis
- Physical Vapor Deposition
- Diff. Scanning Calorimetry
- Small Angle X-ray Scattering
- Electrooptic Characterization
- Spectroscopy
- (UV, vis, IR, fluorescence)
- Microscopy
- (AFM, FCPM, NSOM, POM)
- Holography

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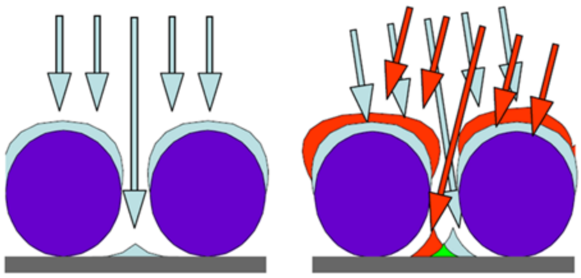
Nanostructure Formation, Nanoanalytics and Photonic Materials

Prof. Dr. Jörg K. N. Lindner

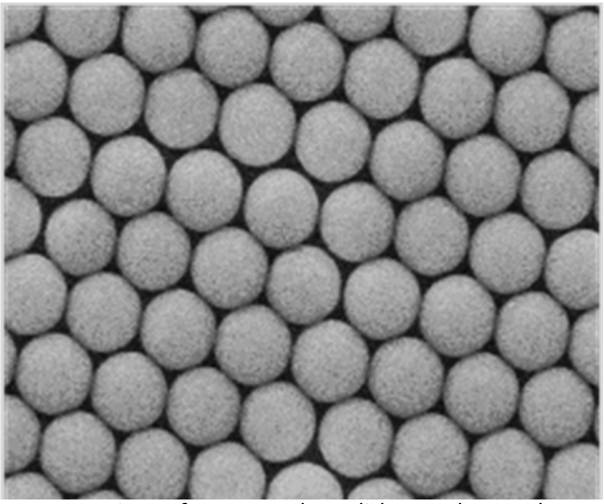
The ability to tailor the morphology, structure and chemical composition of solids at the nanoscale is the key to modern materials design and technology. According to the large variety of different nanostructures presently being investigated for a huge spectrum of applications there is a broad range of formation techniques, which can be used to create them. All of these techniques have in common that precise knowledge of the physical mechanisms acting is required in order to fully exploit their technological potential. Therefore, the interplay between fabrication conditions, resulting nanostructural properties and the macroscopic characteristics involved are studied by our research team in detail. To this end, both microscopic and spectroscopic techniques are employed which allow for a materials characterization at the nanometer or even atomic level. Thereby the emphasis is placed on such materials which are hot candidates for future optoelectronic and photonic devices, including 2D and 3D photonic crystals, plasmonic nanostructures and wide band-gap semiconductor systems. Bottom-up and top-down patterning techniques are combined to obtain nanoscale structures with maximum control at minimum cost.

Nanosphere Lithography



Cross-sectional view of nanosphere lithography beads used as masks in deposition processes.

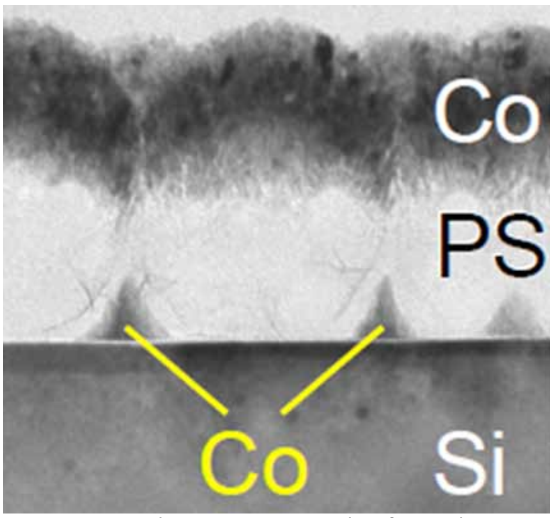
Many applications of nanostructured surfaces today require minimum feature sizes in the range of some ten to a few hundrets of nanometers. Often, either a periodic arrangement of such small motives or at least a surface coverage with a controlled average density of nano-objects is required on a large surface area. Conventional optical lithography does not allow to create features which are much smaller than the wavelength of light used, and lithography systems working in the extreme ultra-violet wavelength region are still under development and will be extremely expensive. Nanostructures can also be created using particle (electron or ion) beams, but such sequential writing techniques are notoriously slow and thus limited to prototype generation.



SEM top-view of a nanosphere lithography mask. Nanoobjects can be formed in the open spaces between each triple of spheres.

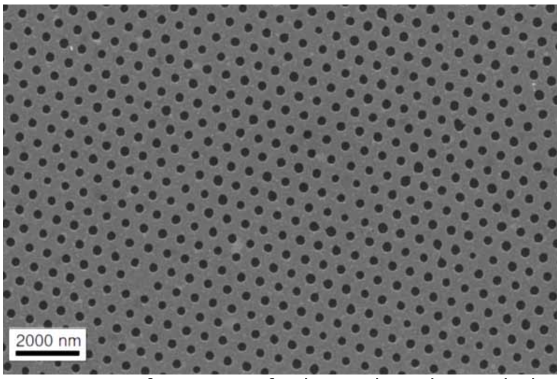
An alternative, cost-effective and materials- general approach to create periodic nanoscale surface patterns is nanosphere lithography (NSL), also called natural lithography. It is based on the fact that whenever objects of equal size and shape can freely move on a surface, they tend to organize themselves in a hexagonally close packed monolayer. If the objects are nanospheres, e.g., from a colloidal suspension, one obtains a sphere array with triangular holes in between each triple of neighbouring spheres. These holes can be used as mask openings, through which small amounts of material can be deposited onto the subjacent substrate or through which the substrate can be modified. Our research team explores techniques to create NSL masks on large substrate areas and with good control of the mask position. Both, plain and prepatterned surfaces are investigated.

Spheres of different materials and diameter are used, typically between 100 and 1000 nm, allowing to adjust the periodicity of patterns to be generated. Here, the expertise developed in the group over the last couple of years to manufacture its own colloidal suspensions is a decisive advantage in the improvement of the NSL technique. Different materials deposition and modification processes are combined with the NSL method in order to explore the potential of the NSL technique. Techniques are being studied which allow to modify the triangular shape of mask openings and thus to enable the generation of much more complex surface nanopatterns.



Cross-sectional TEM micrograph of a polystyrene (PS) mask on silicon, covered with cobalt to create Co nanopyramids.

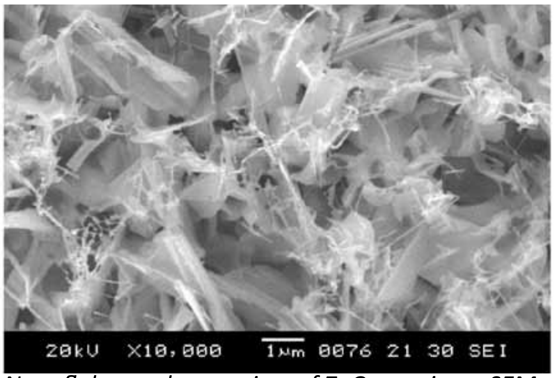
Reactive Ion Etching



SEM image of an array of subwavelength nanoholes in a metallic thin film formed by NSL.

Structures created on top of a substrate surface can be transferred into the near surface region of the substrate using plasma processes. To this end, reactive ion etching RIE is used, in which a superposition of chemical and physical processes is exploited to locally remove atoms or molecules from the surface, resulting in a three-dimensionally nanostructured surface. As our RIE facilities are equipped with a variety of gases, a large number of materials can be nanostructured. The nanostructured surfaces prove themselves to be useful e.g. for (biomimetic) antireflection coatings, as substrates for the localized growth of novel semiconductor nanostructures such as nanodots and nanowires and for the growth of high-quality semiconductor thin films in materials systems with a large crystalline lattice mismatch (nano-heteroepitaxy).

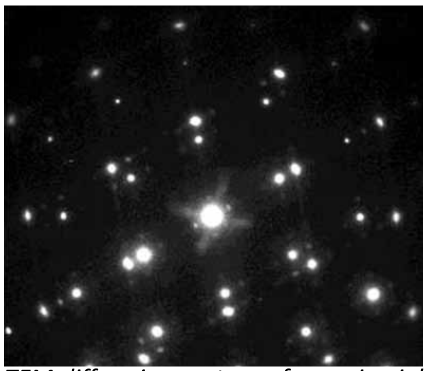
Wide Bandgap Materials



Nanoflakes and nanowires of ZnO seen in an SEM.

Semiconductors with a wide bandgap will be the future material for light generation and may also contribute to photovoltaic solar energy conversion. Among the wide bandgap materials investigated are SiC, which is an indirect semiconductor with outstanding properties for applications as a substrate for other wide bandgap semiconductors, group III-nitrides, which are the basis of today's solid state lighting, and ZnO, which might replace GaN in the near future. GaN thin film growth is studied in a collaboration with the group Prof. Lischka and As, aiming to reduce crystalline defects by the use of nanopatterned substrates. The growth of ZnO nanowires and nanoflakes by means of the vapour-liquid-solid mechanism in a gradient furnace is investigated in order to control the formation of this high-potential optoelectronic material.

Nanoanalytics


TEM diffraction pattern of an epitaxial 3C-SiC film on silicon.

Once a nanostructure or nanomaterial has been created, the external morphology, its internal crystalline structure and the chemical composition need to be analysed. This is particularly important, since at small feature sizes objects are often controlled by their surfaces rather than the bulk and thus are prone to chemical changes. In consequence, macroscopic characteristics, e.g. optical properties, can be extremely sensitive to the chemical surrounding, too. To analyse such properties, scanning electron microscopy (SEM), conventional and high-resolution transmission electron microscopy (TEM) are employed and combined with spectroscopic techniques such as energy dispersive analysis of X-rays (EDX), electron energy loss spectroscopy (EELS) and X-ray photoelectron spectroscopy (XPS).

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- Jens Donitzky
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- Ricarda Maria Kemper
- Prof. Dr. Jörg Lindner
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- Johannes Pauly
- Thomas Schäfer
- PD Dr. Stefan Schweizer
- Werner Sievers
- Stefanie Vogt
- Marie C. Wiegand

Equipment

- Jeol FX2000 S/TEM EDX
- Zeiss EM 902 TEM filtered
- Jeol JSM 6300F SEM
- Jeol 6060 SEM with EDX
- XTEM preparation chain
- Oxford Plasma Etcher RIE80+
- Oxford PECVD 80
- Oxford RIE 100
- Specs/Kratos XPS/ISS
- ODMR, ESR, LM, PL, FTIR.....
- Tube and gradient furnaces

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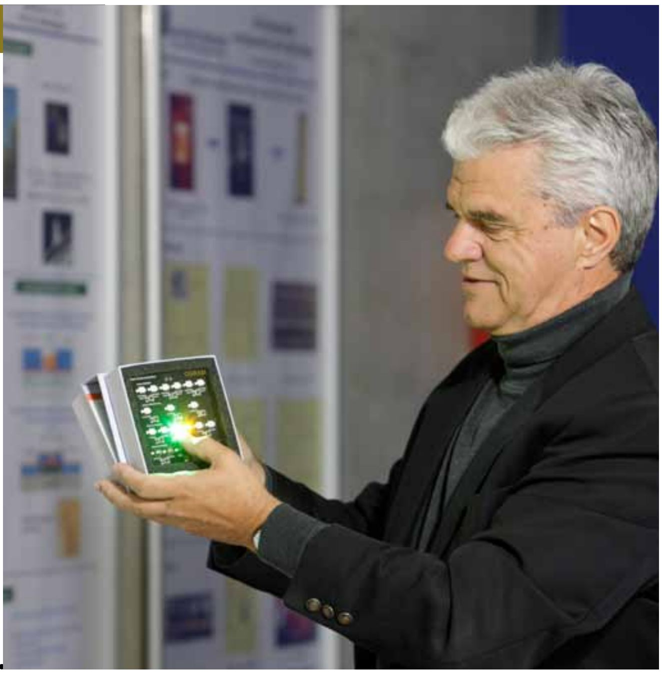
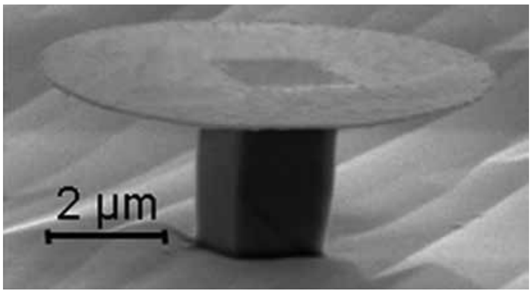
Optoelectronic Semiconductors

Prof. Dr. K. Lischka



The optoelectronic semiconductor group at the University of Paderborn was established in 1993. Since then the group, headed by Prof. Dr. Klaus Lischka, has gained expertise in the growth and characterization of nano-structures of compound semiconduc-tors which find various application in optoelectronic and electronic devices. Molecular beam epitaxy (MBE) sys-tems are used for the growth of vari-ous nanostructures like multi quantum wells and quantum dots. Different methods for in-situ and ex-situ char-acterization are employed to reach optimum quality of device structures which are prepared by high resolu-tion lithography and different etching techniques.

II-VI semiconductor nanodevices for quantum information



Low-threshold microdisk laser.

The concepts of the optical manipulation of quantum states on the nanoscale and corresponding applications in quantum information became a challenging topic in physics. Promising schemes of quantum information processing require indistinguishable photons, identical in frequency and phase, to allow for coherent manipulation of single qubits and to generate entanglement between many of them. Therefore, one of the actual key research objectives is to develop an efficient source of indistinguishable, deterministic single photons which provides excellent mobile qubits. Leading semiconductor-based single photon sources are assembled with quantum dots and excitons bound to impurities. In either case, the indistinguishability of the single photons is still a challenge in all present semiconductor systems but essential for collective manipulation and coupling of many qubits.

A single exciton bound to an isolated fluorine donor in ZnSe (F:ZnSe) provides a physical qubit with potential advantages over previously demonstrated qubits. The F-impurity has a nuclear spin of 1/2 with 100% abundance and is particularly appealing because of its nuclear structure compared to quantum dots. Further, isotopic purification of the ZnSe-host matrix to a nuclear-spin-zero background is possible, eliminating magnetic noise from nuclear spin diffusion.

Recently we have demonstrated indistinguishability between photons generated from two individual F:ZnSe single photon sources which are isolated in nano-resonators. Moreover we were able to switch the quantum interference of the two sources via frequency detuning induced by laser heating. After single photon emission a single electron remains at the fluorine donor, which in moderate magnetic fields provides an accessible two-level system qubit due to the Zeeman-splitting. First magneto-optical experiments with single fluorine donors revealed the potential to allow coherent control of a spin qubit by optical excitation.

These results indicate that fluorine donors in appropriately engineered semiconductor nanostructures can portray atom-like homogeneity and coherence properties, potentially enabling scalable technologies for future large-scale optical quantum computers and quantum communication networks.

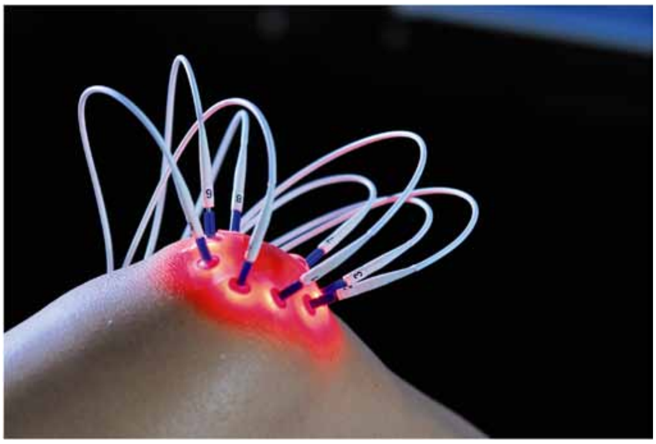
Colloidal nanocrystals embedded in an epitaxially grown semiconductor matrix

We have developed a growth technique which combines wet-chemical growth and molecular beam epitaxy (MBE) to create complex semiconductor nanostructures with nanocrystals as active optical material. We have demonstrated that wet-chemically prepared semiconductor nanocrystals can be incorporated in an epitaxally grown crystalline cap layer. As an exemplary system we have incorporated CdSe nanorods and CdSe (ZnS) core (shell) nanocrystals in a ZnSe matrix with a cap layer thickness exceeding the diameter of the nanocrystals. In contrast to the strain-induced CdSe/ZnSe Stranski-Krastanow growth of a quantum dot layer in a semiconductor heterostructure, our new technique does not rely on strain and thus results in additional degrees of freedom for choosing composition, concentration, shape, and size of the nanocrystals. First results of transmission electron microscopy and X-ray diffractometry show that the ZnSe cap layer is of high crystalline quality and provides all parameters for a consecutive growth of Bragg structures, waveguides, or diode structures for electrical injection.

Bio-Photonics

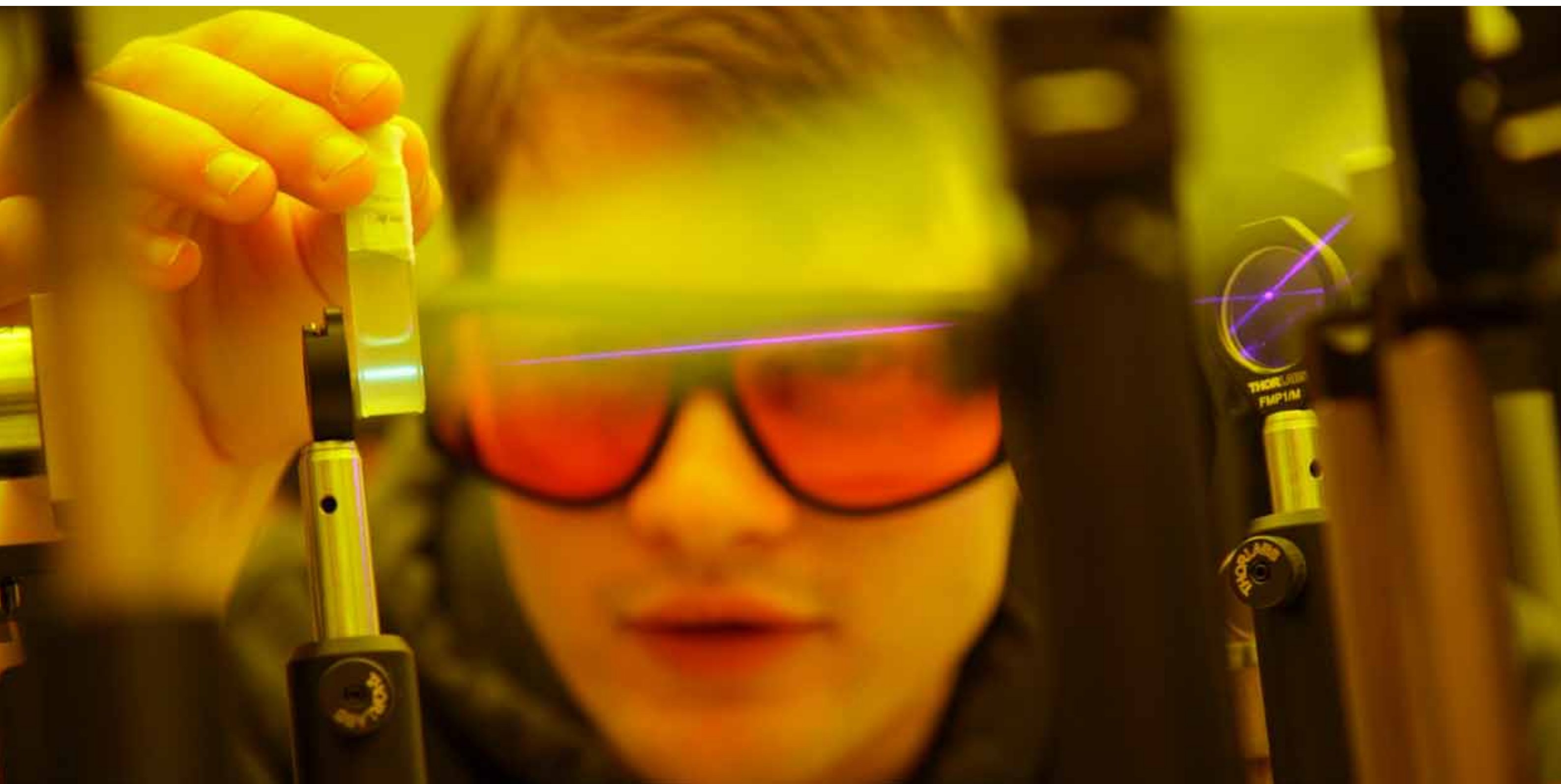
The stimulation of human tissue and cells by laser radiation of different frequency and intensity can induce significant alterations in the metabolism of human cells. These specific effects can be used for the development of new medical therapies.

We investigate systematically the interactions of laser radiation with human tissue and cells and study the elementary effects of laser radiation at a cellular level. We found that the cell metabolism of human osteoblast cells can be increased due to stimulation by intense red laser radiation.



Treatment of osteoarthritis of the knee by non-invasive laser-needles.

A new laser source for such treatments was developed by Dr. Schikora (University of Paderborn) called "laserneedle". Meanwhile the laserneedle technology is medically applied for the treatment of acute and chronic pain, rheumatic syndromes, asthma bronchiale, osteoarthritis, osteonecrosis and some neurological disorders. The application of blue laser radiation in medicine opens new and pain free therapeutic possibilities for the treatment of skin diseases and important dentologic diseases. Our group collaborates with various clinics, universities and research societies in Germany and in Europe, like the University of Munich, University of Jena, University of Bern, University of Innsbruck and the Max-Planck Institute for Biophysics in Frankfurt.



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- Young Min Kim
- Prof. Dr. Klaus Lischka
- Dr. Alexander Pawlis
- Dr. Detlef Schikora
- Olga Reger
- Bernard Volmer
- Tobias Wecker
- Irmgard Zimmermann

Equipment

- Cleanroom
- Molecular beam epitaxy systems (MBE)
- High energy electron diffraction (RHEED)
- Residual gas analysis
- Metal evaporation system
- Optical lithography
- Vacuum-scanning tunneling microscopy
- Scanning electron microscopy
- Microprobe x-ray analysis
- Atomic force microscopy (AFM)
- High resolution X-ray diffraction
- Micro-Photoluminescence

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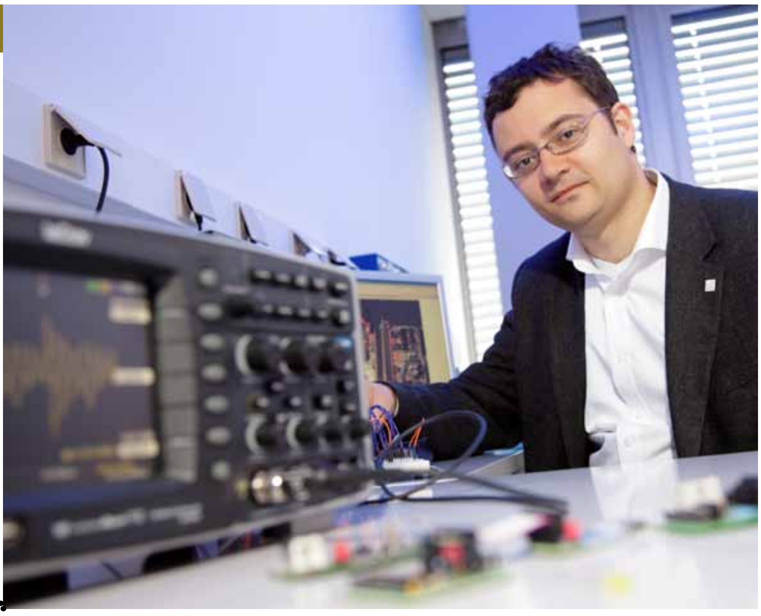
Nanophotonics & Nanomaterials

Prof. Dr. Cedrik Meier



The main research fields of the Nanophotonics & Nanomaterials group are novel materials for applications in nanotechnology and nanophotonic devices. Although both topics are manifold and interesting by itself, the combination of the two often leads to new functionality and effects.

One of the most important technologies for the fabrication of functional structures as base material for photonic or electronic devices is molecular beam epitaxy (MBE). This technique allows for deposition of single crystalline material with atomic layer precision. In the Nanophotonics & Nanomaterials group, this method is used to grow structures made of zinc oxide (ZnO), which is a highly promising base material for future optoelectronics.

Another field of expertise is nanofabrication with various techniques, especially by electron beam lithography and reactive ion etching. This technology allows the definition of nanophotonic devices with feature dimensions in the sub-100 nm regime for a great variety of semiconductors.

Materials for Nanotechnology

Zinc oxide (ZnO) is a highly attractive material for nanophotonic applications. Due to its exciton binding energy of 60meV, which is large in comparison to the thermal energy k_BT at room temperature, it is ideally suited for excitonic applications even at high temperatures. As a metal oxide, it is highly chemically stable and therefore a robust material even in reactive environments.

In order to benefit from these unique features in nanophotonic or electronic devices, molecular beam epitaxy (MBE) is used to create functional layer sequences of ZnO and its ternary alloys (Zn,Cd)O and (Zn,Mg)O, which have a smaller/larger electronic bandgap than ZnO itself. The combination of layers with different material properties like doping or electronic bandgap with atomic precision allows to create functional semiconductor structures like optically active quantum wells or transistor structures. This research is funded within the BMBF NanoFutur program as grant "NanoPhox-Nanophotonic with oxide semiconductors" (FKZ 03X5509).

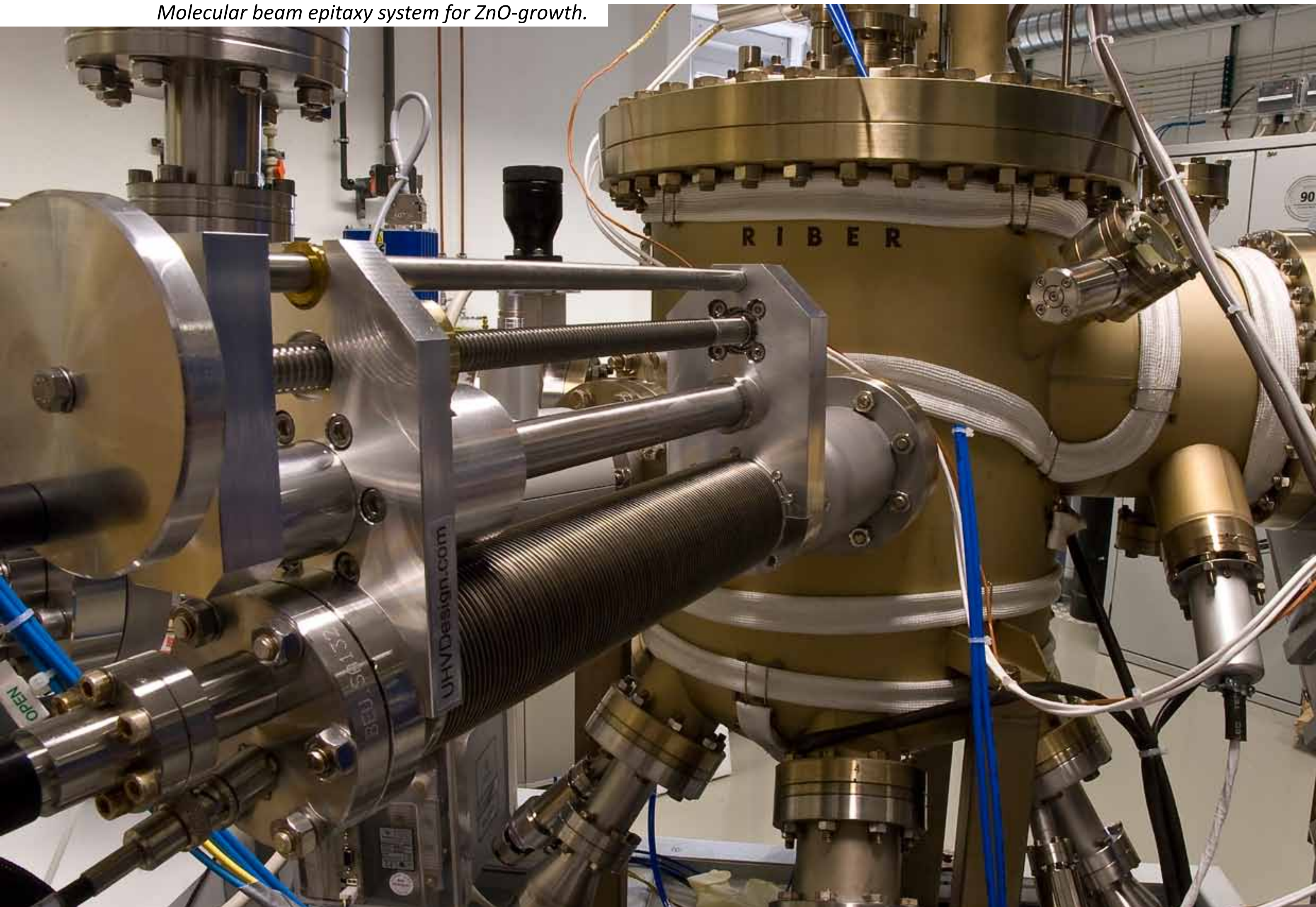
Nanophotonic devices

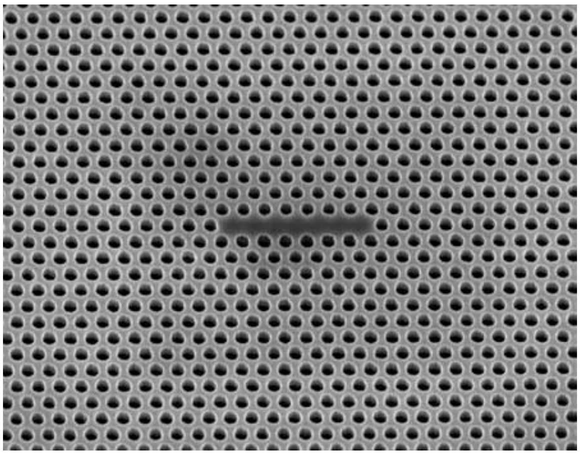
Photonic crystals and photonic resonators such as microdisks allow the control of light-matter-interaction on the nanoscale. This way, novel devices such as nearly threshold-less lasers or devices for quantum information technology like single-photon-sources can be realized.

When semiconductor structures such as quantum wells or quantum dots are used, the excellent properties of such well-defined systems with the tailorability of photonic structures is combined.

A very promising perspective is the combination of photonic devices with functional

Molecular beam epitaxy system for ZnO-growth.





Photonic crystal cavity in GaAs with embedded InAs-quantum dots.

materials. E.g., liquid crystal molecules exhibit a number of interesting properties such as the optical and electrical anisotropy. In their ordered phase, nematic liquid crystals are birefringent, exhibiting an anisotropic dielectric constant. With an applied external electric field, it is possible to control the orientation of the molecules and thus the extraordinary axis of birefingence. When the device is heated above a distinct phase transition temperature (clearing temperature), the order is destroyed and the material becomes isotropic again.

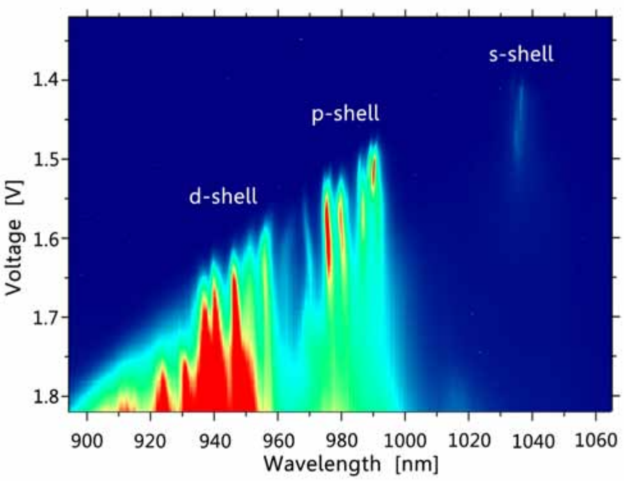
Due to the high refractive index in typical III/V semiconductors such as GaAs, photonic confinement in optical resonators like microdisks is still sustained even when the device is completely immersed into liquid crystal. However, the photonic resonator still interacts with its dielectric environment, the liquid crystal, at the interfaces. Thus, a change in the optical properties of the liquid crystal leads to a change of resonant modes inside the photonic cavity.

This way, by tuning the temperature or the external electric field, the devices show a significant tunability as a function of these external parameters.

Optoelectronic devices on the nanoscale

Self-organized quantum dots are extremely interesting optical emitters in modern semiconductor structures. Due to the strong electronic confinement and the Coulomb interaction, these systems can be regarded as artificial atoms for excitons, which are bound states of electrons and holes.

Many characteristic features of such structures have been shown in the past, namely the orbital shell character (s-shell, p-shell, etc.) and single electron transport through individual quantum dots.



Intentionally positioned quantum dot embedded in a pin-junction.

A great challenge for device technology remains the statistical nature of the growth process: While the self-organization process is a great benefit as it leads to instantaneous formation of a large number of QDs in a single layer, the individual position of the dots is statistically distributed.

Together with the group of Prof. Dr. A. Zrenner, we are investigating device structures provided by our collaboration partners at the Ruhr-University of Bochum (AG Prof. Dr. A. D. Wieck), which combine intentional positioning of individual quantum dots by focused ion beam seeded growth with electrical injection in a pin-diode structure. Using micro-photoluminescence, we were able to detect excitonic states in single quantum dots with electrical injection. The observed shell-filling of orbital states proves that the character of artificial atoms can be transferred to electrically pumped single dot devices.

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- Marcel Ruth
- Igor Tolstoschein
- Nils Weber
- Dennis Wecker

Equipment

- Riber Compact 12 ZnO Molecular Beam Epitaxy
- Oxford Plasmalab 100 ICP-RIE Etching System
- RAITH pioneer Electron-Beam Lithography System
- UV/IR-Micro-Photoluminescence
- Time-resolved Photoluminescence
- Magnetotransport Measurement
- Angular resolved far-field Photoluminescence

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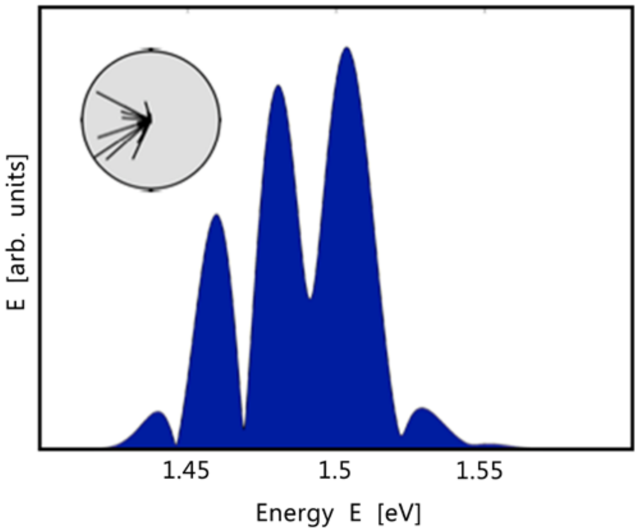
Computational Optoelectronics and Photonics

Prof. Dr. Torsten Meier

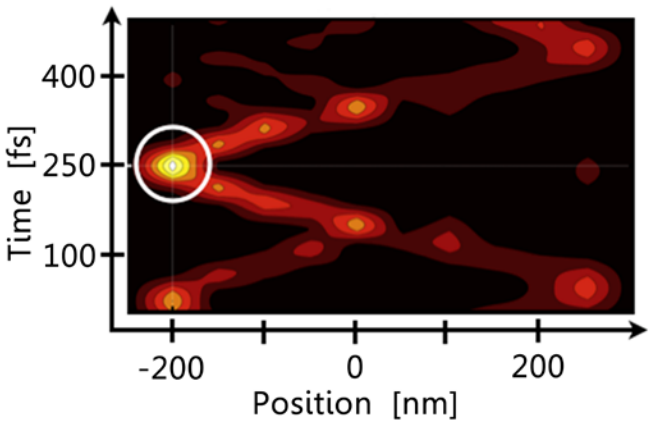
Nanostructures offer the possibility to influence both the electronic states of solid state systems and the electromagnetic fields. Therefore suitably designed hybrid systems allow one to control the light-matter-interaction and thus their optical and electronic properties in fascinating ways. The main goal of our research is the development of microscopic theoretical approaches that are able to accurately describe such optoelectronic nanostructures. In our computations the self-consistent evaluation of the coupled propagation of the electromagnetic field and of the material excitations is often of great importance. The required computer programs, e.g., solvers of Maxwell-Bloch equations are developed in our group. Topics of particular relevance are nonlinear optical effects and the ultrafast coherent dynamics, e.g., Rabi oscillations, photocurrents, wave packet dynamics, etc. Often the obtained results are used to analyze specific measurements or for the prediction of experiments. These studies are performed in collaboration with the DFG-Emmy-Noether junior research group “Computational Nanophotonics” headed by Dr. Jens Förstner.

Motivation

In nanostructured systems it is possible to design many aspects of the optoelectronic properties. On the one hand, structures of reduced dimensionality, such as, quantum wells, wires, and dots, influence the material properties. On the other hand, the electromagnetic field can be tailored by dielectric or plasmonic systems. In both cases the artificial structuring can be used to achieve desired spectral, temporal, or spatial properties of the electronic or photonic system. In our group, we develop theoretical and computational approaches that are able to self-consistently describe such coupled electronic and photonic systems on the basis of microscopic theory.



Spectrum of a laser pulse with the respective phases found by an optimization routine.



If the pulse excites a quantum wire, the electrons are concentrated at a desired location in space and time.

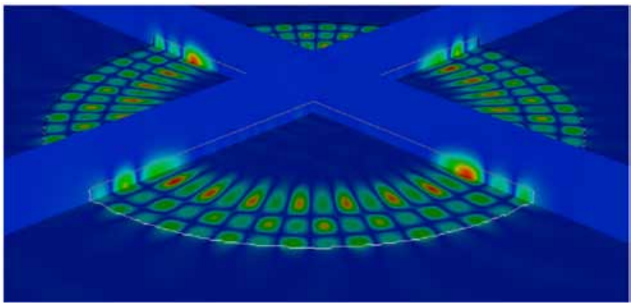
Quantum Dots

The three-dimensional confinement of the electronic states in quantum dots, which are tiny semiconductor nanostructures embedded in a surrounding material, leads to a discrete energy spectrum similar to that found in atoms or molecules. These structures are ideal model systems for fundamental research in the areas of coherent quantum dynamics and many-particle effects and are promising candidates for solid state quantum information processing. Furthermore, quantum dots are already used in a number of applications ranging from solar cells and LEDs to biological research. We study the nonlinear optical properties of quantum dots and specifically many-particle effects - like the electron-phonon interaction - which lead to dephasing of quantum coherence in single quantum dots or ensembles after optical excitation.

Coherent Control

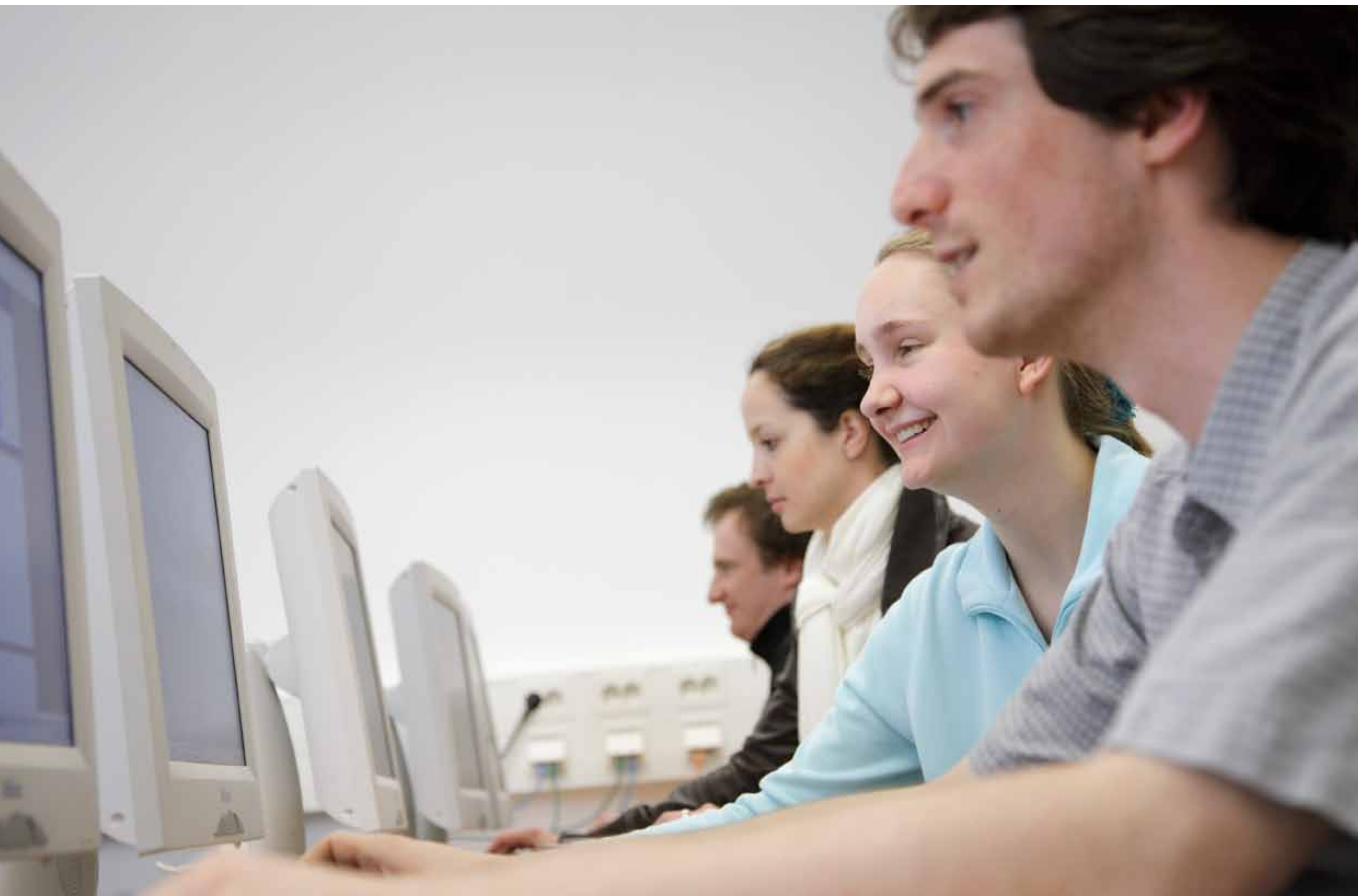
By exciting optical systems with non-trivially shaped laser pulses it is possible to control the spatio-temporal dynamics in the coherent regime. By choosing suitable combinations of frequency components with proper phase relations for the incident laser beam, one can, e.g., generate photocurrents or localize optical excitations at desired spatio-temporal positions. To find the pulse shape that is best suited to achieve a certain goal, numerical optimization routines are used.

Nanophotonics



Whispering gallery mode of a optical micro disk resonator surrounded by a liquid crystal

The distinct size of solid state nanostructures between the atomic scale and the optical wavelength is the basis for their ability to shape and manipulate the light in the near field. In metallic structures, for example, the electronic plasma allows focusing of the light field well into the sub-wavelength regime. Using microscopic theories to describe the nonlinear material response of semiconductor and metal nanosystems in combination with three-dimensional vector Maxwell solvers that describe the propagation of the electromagnetic field we are able to simulate a broad range of nanophotonic materials. Examples are photonic crystals with embedded optical resonators and semiconductor nanostructures, plasmonic metamaterials, microdisks embedded in anisotropic liquid crystals, and hybrid systems.



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- Reinold Podzimski
- Dr. Matthias Reichelt
- Mathias Wand
- Christian Wiebeler
- Franziska Zeuner

Methods

- Microscopic quantum theory for the linear and nonlinear optical properties of nanostructures
- Electromagnetic field simulations in photonic nanostructures
- Application of adaptive and optimization algorithms for computational physics

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Optical Communication and High-Frequency Engineering

Prof. Dr.-Ing. R. Noé

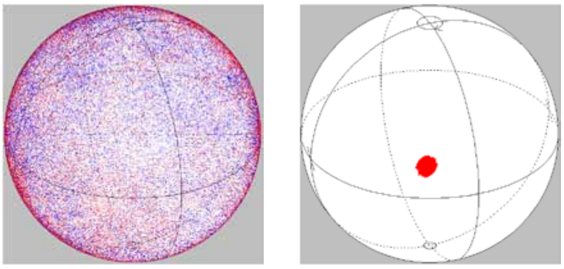
Optical communication transmits information for internet and telephone. At 1.55 µm wavelength the attenuation of optical fibers is so small that after 100 km there is still 1/100 of the transmitted optical power available. The bandwidth is about 1/5 of the light frequency, roughly 40 THz. This is ~1000 times as much as in the whole radio frequency spectrum currently in use. About 4 THz can be utilized very cost-efficiently, by means of optical amplifiers. The superb fiber properties have made internet and low-cost telephony possible. The growth of data communication is enormous, on the order of 50% per year. Network operators and their suppliers want to utilize existing fiber links most efficiently. This defines our research topics: Fiber distortions, i.e., polarization transformations, polarization mode dispersion and chromatic dispersion must be compensated. Advanced optical modulation formats such as quadrature phase shift keying combined with polarization division multiplex allow to multiply optical information density. Phase-noise tolerant coherent receivers provide best performance and allow to equalize the fiber distortions in the electronic domain.

Equalization of Fiber Distortions

Just like a short earthquake excites a distant seismometer for a longer time, short data pulses are temporally broadened in an optical fiber by chromatic dispersion (CD). For compensation purposes we measure CD in a low-cost setup. The pump current of the transmitter laser is slightly modulated at 5 MHz. This causes an optical frequency modulation of a few 100 MHz and hence a pulse arrival time modulation in the presence of CD. At the same time the light power is modulated by about 1%, which provides a reference for synchronous detection. The setup is able to detect periodically repeated light pulse arrival time changes with an accuracy of 100 attoseconds (0,000.000.000.000.000.1 s).

Using DQPSK combined with polarization division multiplex, we have transmitted 5.94 Tbit/s (5.940.000.000.000 bit/s) over 324 km of fiber in the optical C band alone (world record until 2007).

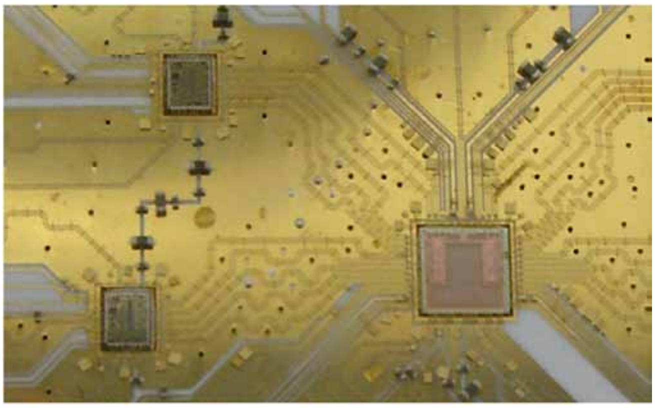
No control **Under control**



Polarization states on Poincaré sphere without (left) and with (right) endless polarization control.

If the fiber core cross section happens to be elliptical rather than circular then the light polarizations corresponding to the ellipse axes propagate with different velocities. This polarization mode dispersion (PMD) also broadens light pulses. We have proposed and the Integrated Optics group has realized an integrated-optical $LiNbO_3$ component by which we compensate PMD. This approach is much more powerful than competing ones, since inside the component several optical polarization controllers are integrated.

PMD varies over time as a function of fiber temperature and handling. Simpler than this, polarization-sensitive optical transmission schemes require an optical polarization control system at the receive end, because otherwise some or most information will be lost. We have realized endless optical polarization control, i.e., with unlimited tracking range, again using $LiNbO_3$ components. IIn this context we have achieved an unrivaled polarization tracking speed of 100 krad/s on the so-called Poincaré sphere. This corresponds to about 8000 complete polarization revolutions per second.



Ceramic board with analog-to-digital converters and „syn-QPSK“ signal processing component.

Optical Modulation Formats

We use 2 orthogonal polarization directions and 4 phase states to transmit in each data symbol 16 different states rather than the traditional 2 (light on/off).

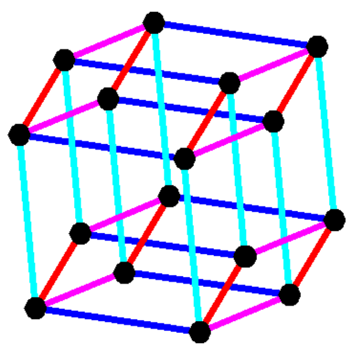
Using this differential quadrature phase shift keying (DQPSK) scheme we have set up a capacity world record in 2005, the transmission of 5,94 Tbit/s (5.940.000.000.000 bit/s) over 324 km of fiber in four spans of 81 km each. At the receive end, polarizations were demultiplexed, and then the data was demodulated in interferometers and regenerated. Recently we have also used our fast endless optical polarization control system for polarization demultiplex. This was successfully tested by Ericsson in the fiber network of Deutsche Telekom.

As an alternative, the 4 phase states can be synchronously demodulated. To this purpose, the light of an unmodulated local laser is superimposed to the received light, thereby creating interferences which depend on the data. Such a coherent optical receiver improves sensitivity and allows for a cost-effective signal equalization, namely against the three above-mentioned fiber distortions.

One key problem is laser phase noise. We have developed a carrier recovery scheme that is extremely phase noise tolerant. Using this scheme we have demonstrated the worldwide first realtime synchronous QPSK transmission with standard lasers. We have then added polarization division multiplex and an automatic electronic polarization control, again as the first worldwide in realtime. The system meanwhile runs with a tracking speed of 40 krad/s and tolerates also polarization-dependent loss. These efforts were funded by the European Commission in project „synQPSK“.

For signal processing we have developed a microelectronic 5-bit analog-to-digital converter for 12.5 GHz sampling frequency in SiGe technology and, together with Prof. Ulrich Rückert, a CMOS chip.

Recently, we have developed an enhancement of the QPSK carrier recovery algorithm which makes it usable for quadrature amplitude modulation formats such as 16-QAM. The latter will allow to double information density once more to 8 bit/symbol. We have also implemented this algorithm in an FPGA and conducted the worldwide first realtime transmission of synchronous optical 16-QAM with large phase noise tolerance.



Projection of a hypercube with 16 optical “synQPSK” symbols in the 4-dimensional space of two quadratures and two polarizations onto a 2-dimensional plane.

Equipment

- 40 DWDM lasers
- Tunable lasers
- 40 and 10 Gbaud optical test beds
- Coherent optical test
- 50 GHz oscilloscopes
- 8 GHz realtime oscilloscope
- 110 GHz network analyzer
- Microwave and millimeter wave generators
- Optical spectrum analyzers
- Optical wavemeters
- 420 km of optical fiber
- Recirculating loop switch
- Erbium-doped fiber and Raman optical amplifiers
- Fixed and variable optical dispersion compensators
- Polarimeters
- Electrooptic polarization controllers
- Interferometers
- Optical fiber splicers
- Semi-automatic wedge bonder
- Climate chamber
- Microscopes
- Workstations
- RF and IC design software
- Optical system simulation software

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Theoretical Optoelectronics and Photonics

Prof. Dr. S. Schumacher

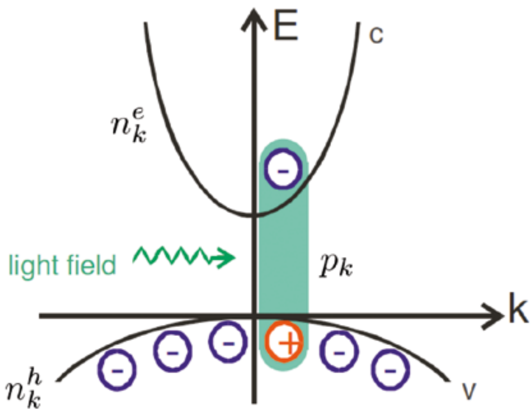
Nanostructured semiconductors, nowadays play a crucial role in optoelectronics and photonics and have become indespensible in our everyday life. From a fundamental perspective, the optical properties of these systems are dominated by complicated excitations inside the semiconductor material, the details of which can often not be understood within simple models.

The focus of the Theoretical Optoelectronics & Photonics group's research is on the development of microscopic theories, describing the nonlinear optical excitation dynamics in semiconductor nanosystems down to ultrashort timescales. Systems we study are based on inorganic as well as on organic semiconductors at the interface between physics and chemistry.

Together with experiments we use our theories to gain insight into microscopic physical mechanisms underlying a system's optical properties. Beyond pure fundamental research, we combine our understanding of nonlinear light-matter interaction with design possibilities for electronic states and photonic modes in nano- or microstructured materials. This, for example, can lead us to develop strategies for novel light manipulation schemes such as all-optical amplifiers and switches.

Introduction

$$i\hbar\frac{d}{dt}\Psi = \hat{H}\Psi$$



In our group, we have a strong expertise in developing microscopic theories that accurately describe the interaction of (laser) light fields with the electronic many-particle system in semiconductor nanostructures, such as quantum-wells and quantum dots and different molecular systems on the nanometer scale. Based on these theories, we can compute the optically induced excitation dynamics, where appropriate, self-consistently together with the description of the propagating light fields. Depending on the system's complexity, we combine these calculations with different electronic structure methods to accurately calculate the confined electronic states inside the nanostructure.

Nonlinear Photonics

In the area of photonics, in addition to designing the electronic states in a given nanostructure, we aim to design the propagation of light through the system. In our work, we are particularly keen to design the system such that semiconductor-specific many-particle interactions can be utilized in novel light manipulation schemes, such as all-optical switches or amplifiers.

An example from our work is shown in Figure 1, where the strong coupling of a semiconductor quantum-well exciton to a confined optical mode is used to supress unwanted and harness desirable aspects in the complex nonlinear system response. This way it was possible to design a low-light-intensity all-optical switch with transistor-like output performance in the theoretical calculations. Part of this work is carried out together with Rolf Binder (University of Arizona, USA) and Nai Kwong (Chinese Univ. of Hong Kong).

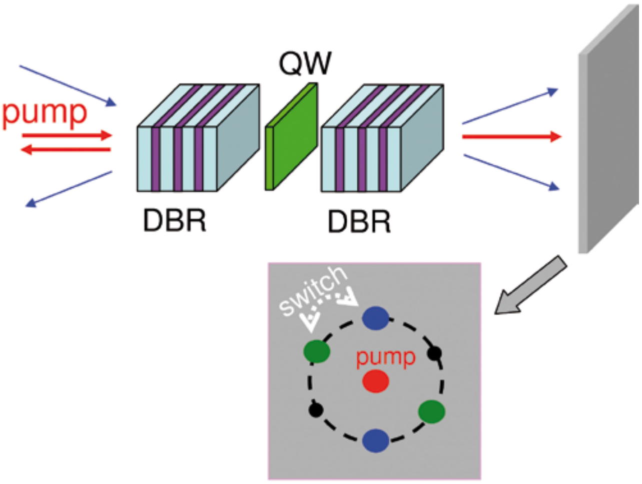
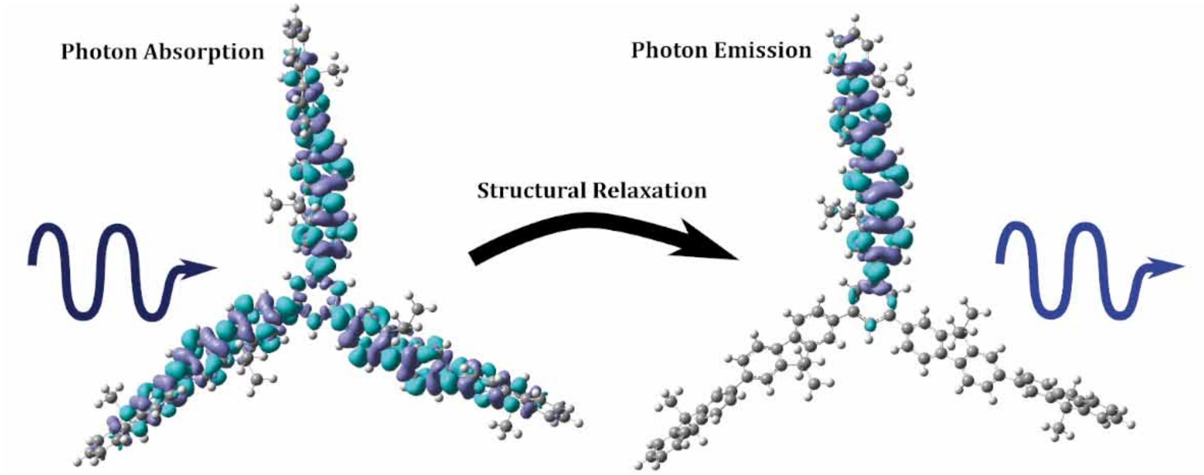


Fig. 1: All-optical switch based on transverse polariton patterns.

Photophysics of Conjugated Polymers

As a newly emerging class of materials, semiconducting conjugated polymers have recently become of great interest. These materials combine the flexibility of plastics (easy to process, non-toxic, cheap) with desirable electronic and optical properties for a large variety of applications in optoelectronics and photonics.

We study the photophysics of different conjugated polymers. We investigate these molecular systems using high-level quantum-chemical methods and develop models to study their nonlinear optical properties.



In a future project, we have also planned to investigate inorganic/organic hybrid systems, where molecules are included as photoactive components in otherwise crystalline photonic structures. Part of this work is done together with Ian Galbraith's group at Heriot-Watt University (UK) and with Ifor Samuel's group at St. Andrews University, providing us with the right mix of theoretical and experimental expertise.

Graphene Nanostructures

A semiconductor with exceptional properties and that is two-dimensional to begin with is graphene. However, due to its zero fundamental bandgap energy, processes that determine the optical properties of graphene can be very much different from what we got accustomed to in other semiconductor materials. In nanostructured graphene, however, such as graphene nanoribbons, nanoflakes, and carbon-nanotubes, a fundamental energy gap can open up, such that electronic transitions across this gap can efficiently couple to optical fields with frequencies in the visible spectral range. We study a variety of these carbon nanostructures in view of their potential for certain optoelectronics applications.

As an example we predict a circular photogalvanic effect in carbon nanotubes which has previously been studied in semiconductor quantum-wells. A schematic illustration is shown in Figure 2 and calculated data is shown in Figure 3.

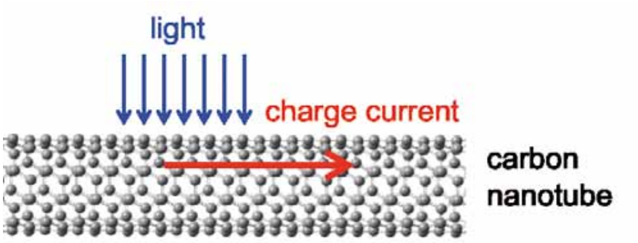


Fig. 2: Photogalvanic effect in a semiconducting carbon nanotube without inversion symmetry.

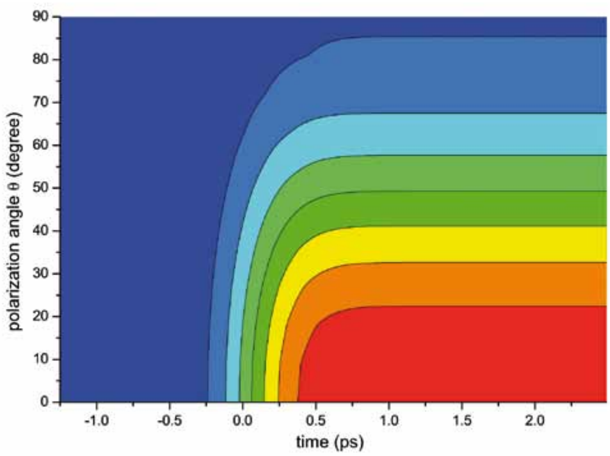
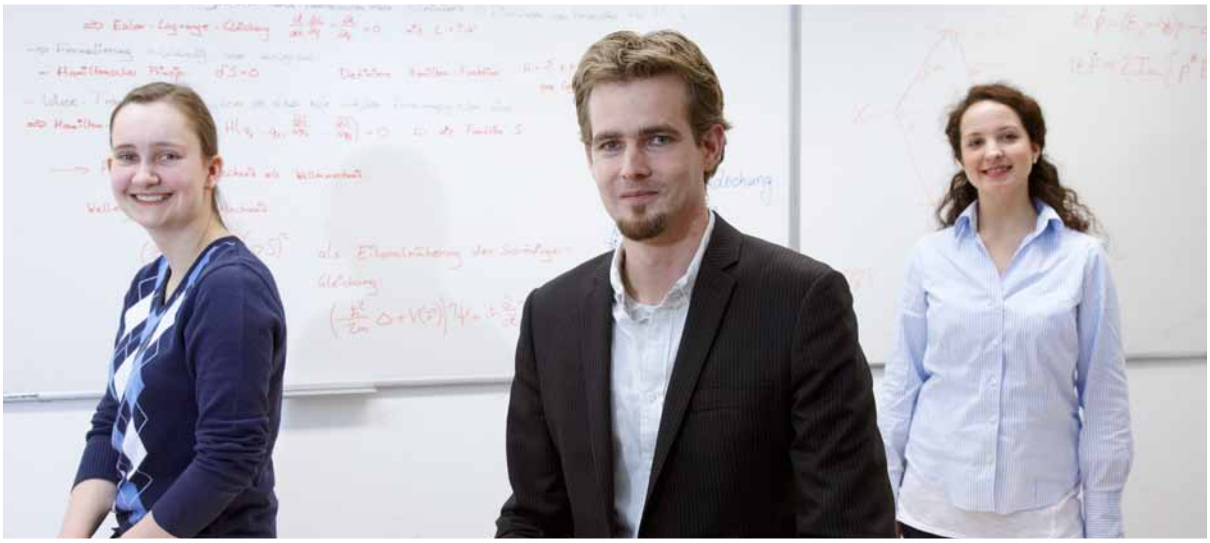


Fig. 3: Photocurrent in a semiconducting carbon nanotube for different angles of incidence for a circularly polarized 1ps light pulse.



Group Members

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- Christian Hölscher
- Regina Kruse
- Przemyslaw Lewandowski
- Andreas Lücke
- Jun.-Prof. Dr. Stefan Schumacher

Methods

- Microscopic quantum-mechanical models of electronic excitations in semiconductor nanostructures.
- Ab-initio quantum-chemical methods for electronic states and excitations in molecular nanosystems.
- Electromagnetic field simulation in photonic structures.

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Integrated Quantum Optics

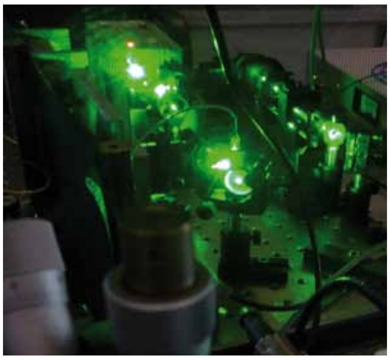
Prof. Dr. C. Silberhorn

Photo: DFG/Ausserhofer

The research activities of the integrated quantum optics group are directed towards the implementation of advanced photonic quantum systems for applications in quantum information processing and other optically based quantum technologies. Our goal is to realize systems, which exhibit increased complexities in terms of number of channels, input states and non-classical properties. The quantum character of light is explored by studying particle-like as well as wave-like properties. To this end we employ tailored integrated optics devices, ultrafast pump pulses as well as photon number resolved detection.

While integrated optics significantly reduces the experimental effort for the realization of sources of quantum states and quantum circuits with multiple channels, employing ultrafast pulses as quantum states enables not only the synchronization of creation and detection events within one quantum system. It also allows running quantum communication systems at high clock rates and time-multiplexed setups. In addition the rich spectral structure of ultrafast quantum light pulses can be exploited for channel multiplexing and studies of higher dimensional systems.

Fabrication of integrated devices

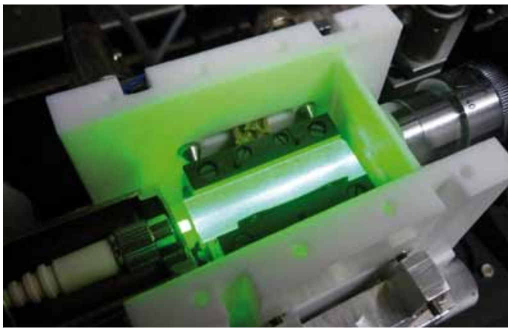


Our group deploys and improves techniques for the fabrication of integrated optical waveguide devices in lithium niobate ($LiNbO_3$). Among them are wafer-dicing and polishing, indiffusion of Titanium and laser active ions, different ion-exchange procedures, electric field and UV-assisted periodic poling of ferroelectric domains, selective wet-etching of microstructures, ion beam etching of nanostructures, deposition of thin metal films and dielectric mirrors, etc..

For future implementation of novel quantum applications, we concentrate on producing poling structures with shorter periodicities and improved optical coupling to fibers. In addition, we focus on enhancing process efficiencies inside the optical waveguides.

Only recently we extended our spectrum of applications by introducing potassium titanyl phosphate (KTP), which complements our well-established material system $LiNbO_3$.

Integrated quantum sources

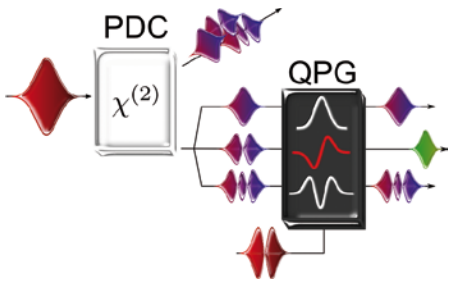


Waveguides in periodically poled $Ti:LiNbO_3$ (Ti:PPLN) and reverse proton exchanged $LiNbO_3$ (RPE:PPLN) are the basic structures for nonlinear quantum state preparation via parametric down-conversion (PDC).

In particular the implementation of two color PDC sources is of interest when addressing rare earth ionic quantum memories used in quantum repeaters. One generated photon of a distinct wavelength, which is matched to an atomic transition, is stored in an ionic trap, while the other photon – ideally in the telecom wavelength regime – can be efficiently transmitted in optical fibers.

Recent research activities concentrate on the fully integrated generation not only of photon pairs but of photon triplets. With this approach the generation of heralded photon pairs becomes feasible. Another activity focuses on the development of integrated sources of entangled photon pairs based on PDC in specifically tailored PPLN waveguide structures.

Pulsed quantum light



Ultrafast pulsed quantum states of light, which are generated in the process of parametric downconversion (PDC), intrinsically feature multiple broadband spectral modes. In addition, they form a basis of quantum communication systems at high clock rates. Our research activities are focused on further increasing the available qubit rates by making this intrinsic broadband mode structure accessible for information coding. The PDC states generated in our laboratories are ideally suited for this task as they provide multiple broadband modes for efficient channel multiplexing.

In this context we introduced quantum pulse gates and quantum pulse shapers, devices based on engineered frequency translation processes. They enable us to address, modify and interconvert individual broadband spectral modes and thus allow for complete ontrol over the broadband spectral mode structure of ultrafast quantum light pulses.

State characterization

Quantum state characterization is essential for many quantum optical applications. The standard technique, homodyne detection, measures the distribution of field quadratures and determines their quasi-probability distribution, the Wigner function. However, the method relies on tomographic reconstruction, since the Heisenberg uncertainty principle precludes simultaneous measurement of field quadratures.

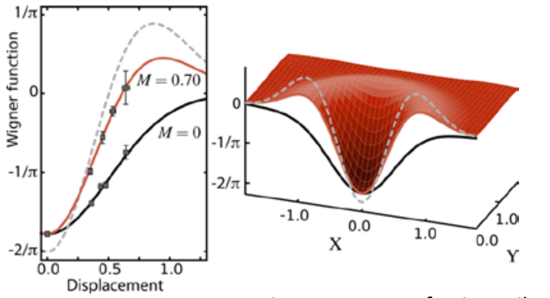
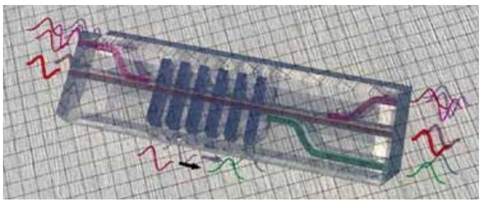


Figure courtesy of Kaisa Laiho.

Nevertheless, the determination of single points in phase space is possible by utilizing photon counting. We have implemented a scheme to measure the Wigner function of spectrally broadband, pulsed single photons at individual points in phase space. The method allows us to verify the non-classicality of states and directly investigate the photon number statistics of displaced states [1].

Interfaces

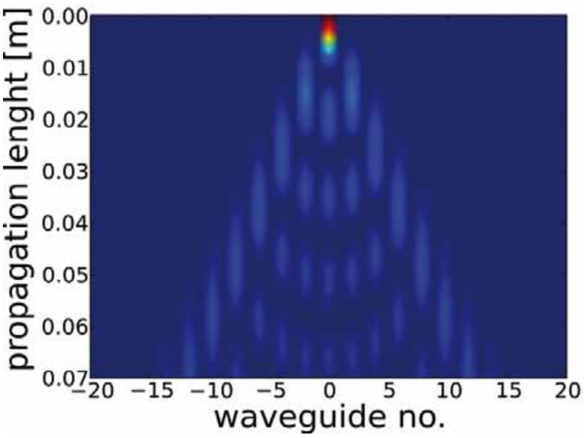


Future quantum networks, which combine quantum memories and photonic channels for qubit transmission, also require interfaces to efficiently transduce quantum information between different nodes of the network. While promising candidates for quantum memories (e.g., trapped ions) can only be addressed in the UV- and visible spectral region, efficient long distance photonic state transfer is only possible at telecommunication wavelengths.

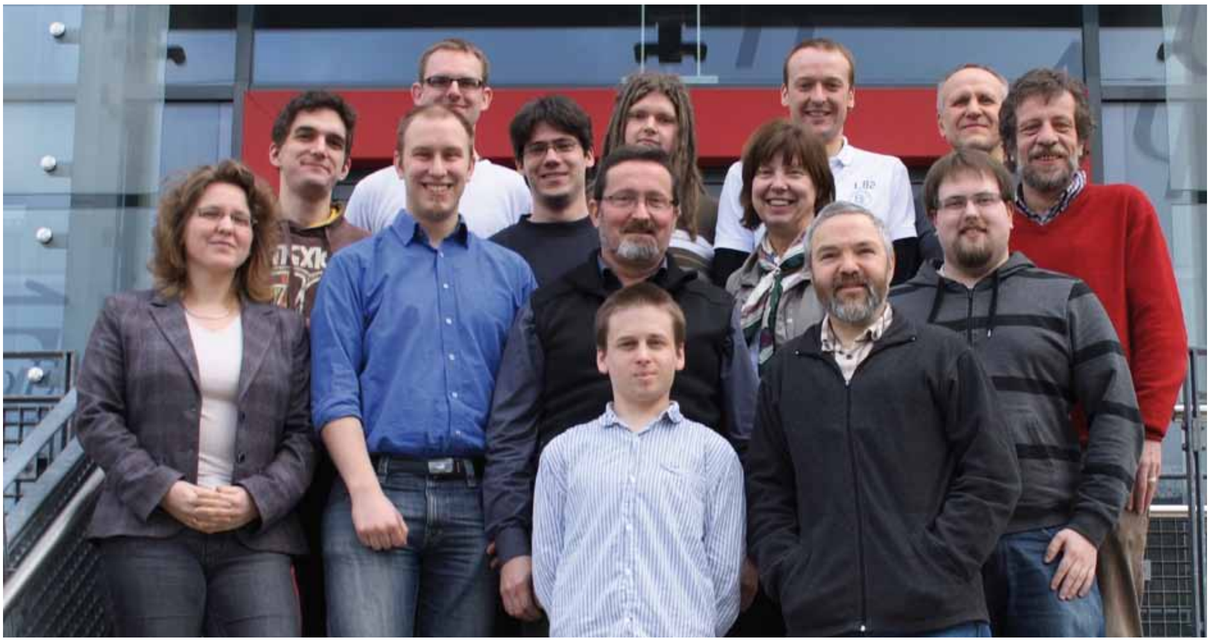
Our goal is to use engineered integrated nonlinear optics to bridge this gap. Special focus lies on the interconversion between the Yb^{2+}-transition at 369.5nm and the 1310nm telecommunication window for use in a continuous variable quantum repeater protocol. We employ KTP waveguides, which we only recently added to our fabrication capabilities. With those we aim to reach conversion efficiencies close to unity.

Quantum walks

Quantum walks have been proven to be a universal resource for quantum computation. We are implementing a quantum walk by means of integrated optics on a miniaturized chip. The walk is realized inside an array of homogenous waveguides, which are coupled by the evanescent field overlap of the guided modes. This waveguide array is capable of creating highly complex, spatially entangled quantum states, which are perfectly suited for applications in quantum computing and quantum simulation.



[1] K. Laiho et al., PRL **105**, 253603 (2010).



Group Members

- Christine Silberhorn
- Irmgard Zimmermann
- Hubertus Suche
- Harald Herrmann
- Benjamin Brecht
- Andreas Christ
- Fabian Elster
- Georg Harder
- Stephan Krapick
- Helge Rütz
- Christof Eigner
- Viktor Quiring
- Raimund Ricken
- Maximilian Hake
- Sebastian Morgenstern

Equipment

- Cleanroom facilities for waveguide production
- Quantum optical laboratory with several ultrafast laser systems
- Multiple cw laser sources at numerous wavelengths
- Single photon detectors (VIS and IR)
- Equipment for sample characterization (linear as well as nonlinear)

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High-Frequency Electronics

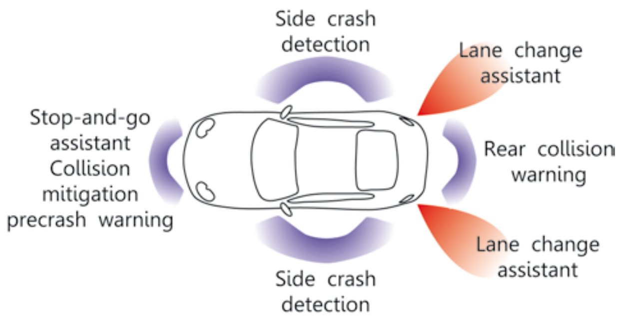
Prof. Dr.-Ing. A. Thiede

The High-Frequency Electronics group is mainly focused on the design of monolithically integrated circuits for applications in the high frequency domain, currently in particular for optical communications and sensorics.

Commercial standard software tools such as Cadence Design Framework and Agilent Advanced Design System are used. The access to leading edge foundries such as ST-Microelectronics, Infineon, IHP and OMMIC allows the chip fabrication in a variety of semiconductor technologies ranging from Si-CMOS over SiGe-HBT up to GaAs-HEMT. The group's measurement laboratory is equipped for on-wafer characterization up to 110 GHz in time domain and up to 40 GHz in frequency domain.

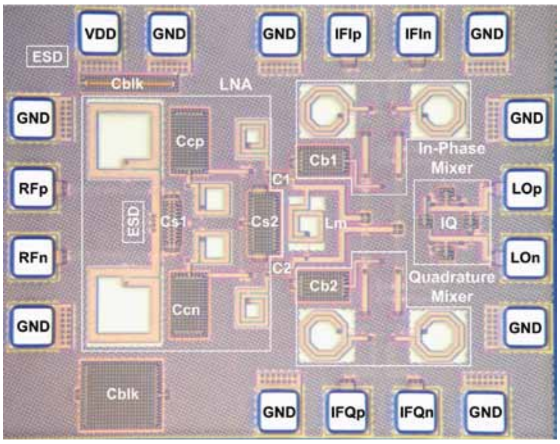
In the BMBF funded joint project PIDEA the group presently works on a 24 GHz narrow band FM-CW radar system in Si CMOS technology for automotive and industrial use. Furthermore, two DFG-funded projects target integrated active sensors for electromagnetic near field scanners and 110 Gbit/s decision feedback equalizers for the optical Ethernet.

24 GHz Car Radar



Driver assistance systems are one approach of the EU to combat the still high number of persons severely injured or even killed in car accidents year by year. The challenging system integration, not only with respect to technical but also economical issues, gave reason for the European PIDEA project EMCPack FASMZS. Managed by Fraunhofer ENAS/ASE, Paderborn and Infineon Technologies AG, Munich, University of Paderborn collaborates with Hella KGaA Hueck & Co, Lippstadt and InnoSenT GmbH, Donnersdorf. The targeted 24 GHz FM-CW radar will find multiple uses in the car as illustrated above, while long range automatic cruise control still keeps a domain of 78 GHz systems.

For 24 GHz, ASICs are to be developed by Infineon in close cooperation with Paderborn University and fabricated in Infineon's 0.13 µm CMOS process. A two chip solution, i.e. a transmitter with LO and power amplifier and a receiver with LNA and mixer is intended.



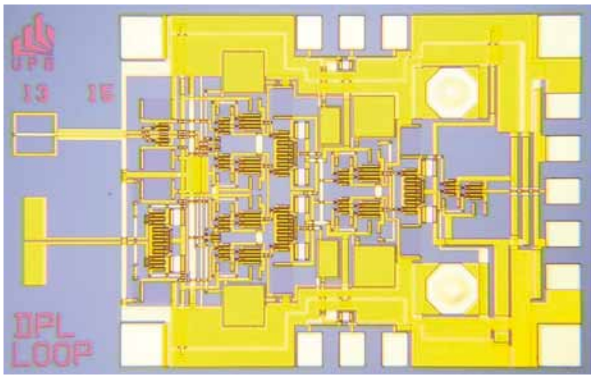
The depicted 0.48 mm2 I/Q-receiver comprises a low noise amplifier with pseudo-differential two stage configuration, current reuse technique and ESD circuitry, two Gilbert cell mixers, and a passive polyphase filter. The chip was fabricated in Infineon's standard 0.13 µm CMOS technology with 6 Cu layers and 1 Al pad top level. At 24 GHz a conversion gain of 18 dB with 5 dB NF have been achieved at a power dissipation of 24 mW from a 1.5 V supply. The input-referred 1 dB compression point and IIP3 have been measured at -26.8 dBm and -17.7 dBm, respectively.

The major challenge to down-conversion mixers in CMOS is the excessive flicker noise. The corner frequencies of the used process are above 50 MHz, thus posing a considerable obstacle for base-band conversion to the range from 50 Hz to 10 kHz. To overcome this problem, besides Gilbert cell mixers, balanced resistive mixers consisting of unbiased MOS transistors have been developed. In the latter passive mixers, an active channel and thus its noise contribution are avoided. Additional significant advantages are minimal power consumption and simplicity of realisation.

Electromagnetic Field Sensors

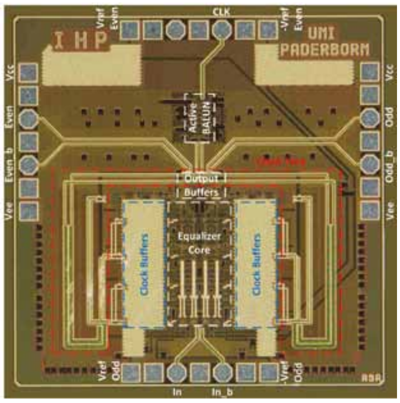
Near-field measurements of printed circuit boards and large-scale integrated circuits are gathering increasing interest as an effective technique for detecting electromagnetic noise emission sources. The high frequencies used in modern electronic products carrying analogue, digital or mixed signals have led to high electromagnetic emissions and weak susceptibilities resulting in the crucial problems of electromagnetic interference (EMI) and compatibility (EMC). Furthermore, understanding of EM field distribution and EMC is necessary from the very beginning of the design process for the development and verification of models, which are required for a dedicated model based development of new components using complex structures.

Due to fine geometries of today's PCBs or even ICs, small field probes exhibiting high



spatial resolution are of interest. Unfortunately, decreasing probe sizes lead to reduced sensitivity, so that the measurement of electromagnetic field distributions with high spatial resolution becomes a challenging task. A promising approach to obtain highly resolved field data with increased sensitivity is the use of miniature active probes including not only the sensing part of the probe but also active circuitry such as preamplifier. The figure exemplifies a magnetic loop and electric dipole double probe integrated with switchable matched common source and common gate broad band amplifiers.

110 Gbit/s Data Decision



In optical high speed, not only but in particular long haul communication systems, insufficient receiver bandwidth, Chromatic Dispersion (CD) and Polarization mode dispersion (PMD) result in Intersymbol Interference (ISI) in the received signal. To compensate in particular the time varying PMD and its effects adaptively, optical and electrical methods can be used. However electrical methods have advantages in terms of cost efficiency, size, easy integration into the receiver and easy adaptation to the varying conditions in the optical fiber. Besides linear FIR filters, nonlinear Decision Feedback Equalizers (DFE) have proven to be an effective method to compensate ISI. Based on first demonstrators at 10 Gbit/s and 20 Gbit/s in GaAs HEMT technology, a further improved concept was implemented in a 0.13 µm SiGe HBT technology. Test circuits operating up to 110 Gbit/s input data rate have been demonstrated.

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- Matthias Krumme
- Ahmed Awny
- Vadim Issakov
- Ragini Shukla
- Nasir Uddin

Equipment

- 50 GHz Sampling Scope
- 4x12.5 Gbit/s PRBS-Gen.
- 43 Gbit/s 4:1 Mux
- 12.5 Gbit/s Error Detector
- 40 GHz VNA
- 40 GHz Spectrum Analyzer
- 110 GHz Signal Generator
- 110 GHz Wafer Prober

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Ultrafast Nanophotonics

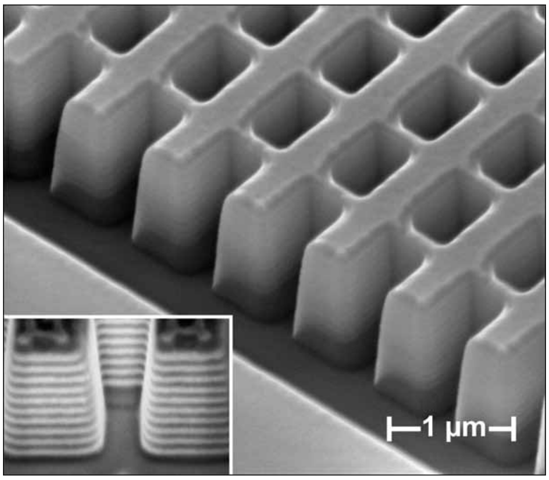
Prof. Dr. Thomas Zentgraf

The newly established Ultrafast Nanophotonics group at the University of Paderborn focuses its research on optical properties of artificial material system. Modern nanotechnology opens the possibility to manipulate the arrangement and structure of natural materials down to the nanoscale comparable to the optical wavelength. This freedom allows a direct engineering of the optical material properties that can be utilized for a new class of photonic devices and applications.

The characterization of the optical properties of such material systems plays an important role for the further design and to proof principle concepts arising from new physical effects. Ultrafast spectroscopy is the key in order to understand the underlying processes in these materials that lead to the desired functionality.

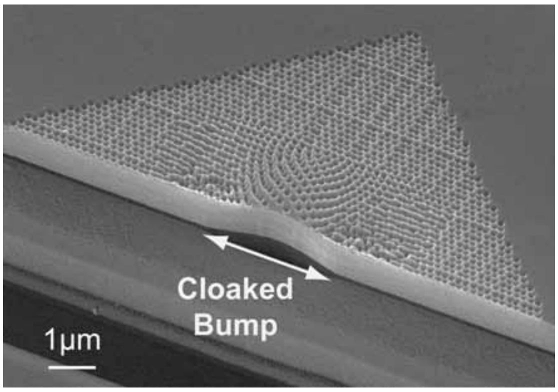
In combination with strongly confined optical fields based on Plasmonic excitations these materials posses the potential for highly compact and ultrafast optical devices.

Novel optical material concepts and design methods



Metamaterial with a negative index of refraction.

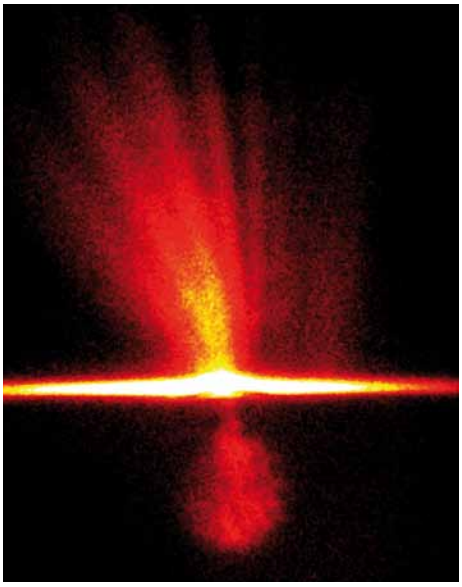
The availability of optical materials with user-defined optical properties that would fulfil perfectly the requirements of applications are highly desired in the photonics industry. The lack of such materials limits realization of optical devices. With the progress in nanofabrication technology we are now confronted with the ability to freely engineer artificial nanostructures down to a few nanometers well below the optical wavelength. Such materials, if designed properly, can exhibit completely new optical properties that are not available by any natural material. The best known example is the negative index of refraction. By utilizing strong localized fields in dielectric and metallic nanostructures the effective material parameters can be nearly arbitrary altered and in that way new optical materials designed. The Ultrafast Nanophotonics group designs, fabricates, and investigates such new optical materials based on plasmonic nanostructures for the near-infrared wavelength domain. In combination with newly developed design methodologies like the recently introduced concept of Transformation Optics open the possibility to obtain new functionalities for optical elements or even allow the realization of astonishing effects like invisibility (cloaking). First cloaking devices could be already demonstrated within a relatively simple nanostructured silicon slab waveguide.



Optical “carpet” cloak based on nanostructured silicon.

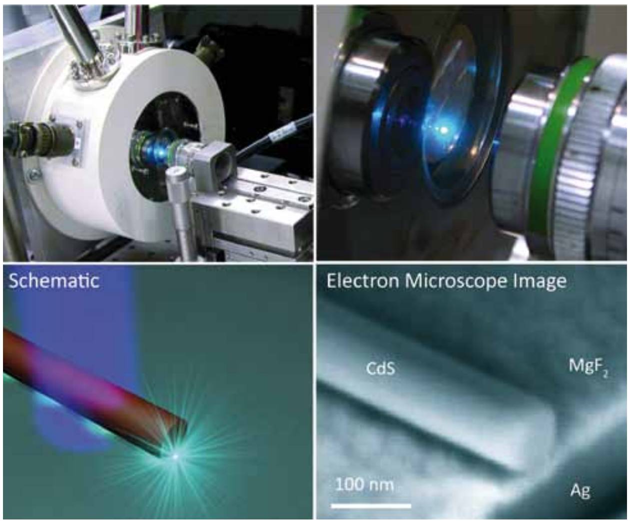
Plasmonic devices

Confining optical fields to extremely small volumes is one of the biggest challenge in order to miniaturize optical elements down to a chip level to be comparable in size with electronic elements like the transistor. Here, the excitation of electronic surface states on a metal-dielectric interface might open a new way for guiding light in extremely small volumes without losing the possibility of high speed operation. However, these electronic excitations, so-called Surface Plasmon Polaritons, are inherently lossy and signals can be transferred only over short distances. In our group we evaluated new concepts in altering the propagation of these Plasmons by modifying the dielectric material on top of the metal on a nanometer scale.



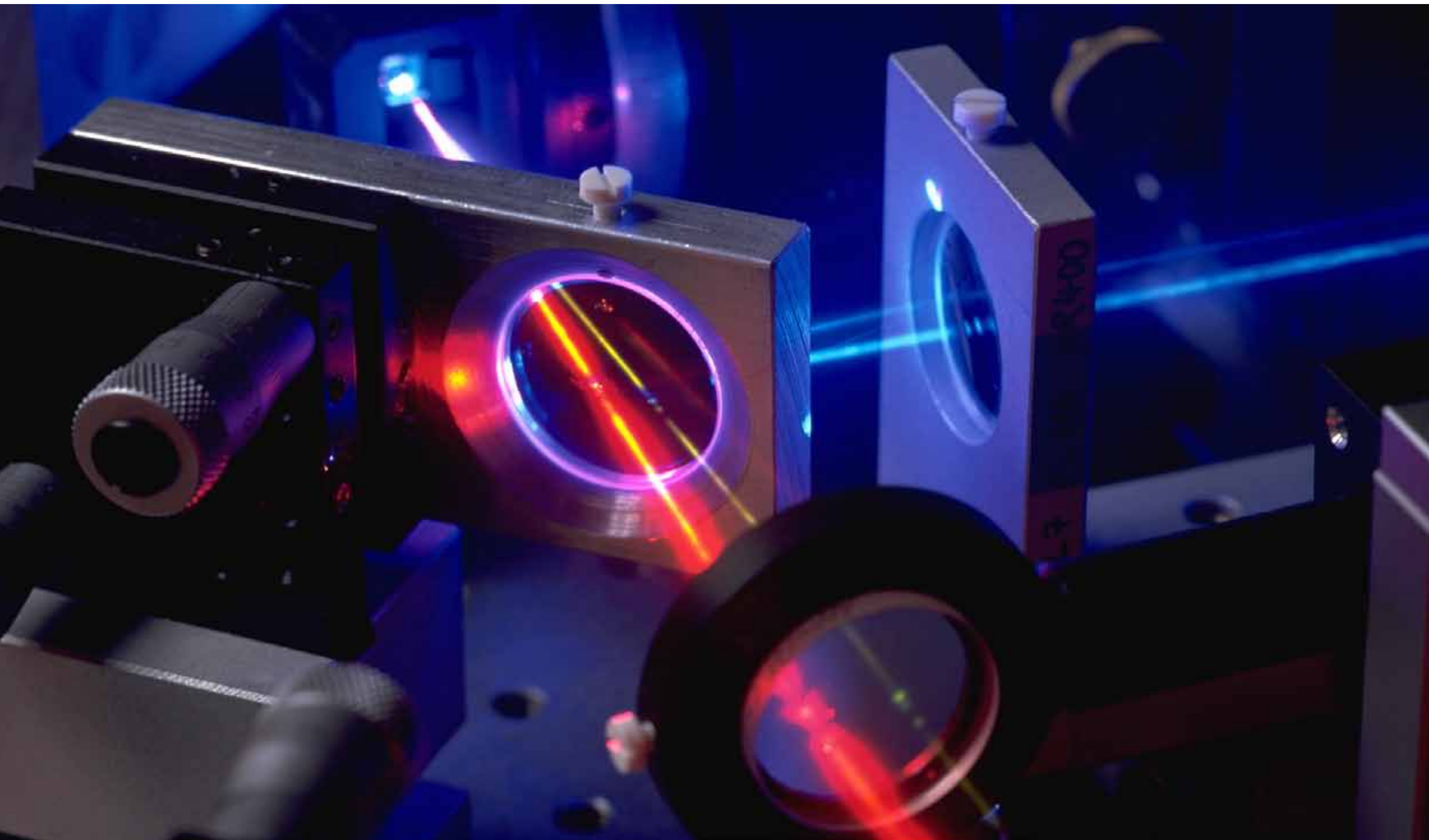
Surface plasmon propagating through a plasmonic Luneburg lens.

Ultrasmall light sources



Plasmonic nanolaser with emission at 490nm.

Many optical applications require small and highly efficient optical light sources. In particular quantum optical and on-chip devices would greatly profit from ultrasmall sources. However, the efficiency of conventional light emitters is in general extremely poor. Our research activities in the field of ultrasmall light sources are therefore focused mainly on strategies of enhancing the emission efficiency by directly modifying the emission characteristic by plasmonic nanoantennas or by utilizing the strong confinement and large radiation enhancement of Surface Plasmon Polaritons to increase the emission only in particular optical modes. Therefore, we employ also nonlinear and time-resolved techniques, which have the potential to provide new inside the emission modification or the mode structure of the design nanoscale system.



Group Members

- Andreas Herbst
- M.Sc. Holger Mühlenbernd
- Prof. Dr. Thomas Zentgraf

Equipment

- Time resolved optical spectroscopy
- Photon correlation spectroscopy
- fs nonlinear spectroscopy
- fs Laser sources for VIS/NIR
- Optical microscopy
- Transmission spectroscopy for UV, VIS, and NIR
- Phase sensitive spectroscopy for NIR.

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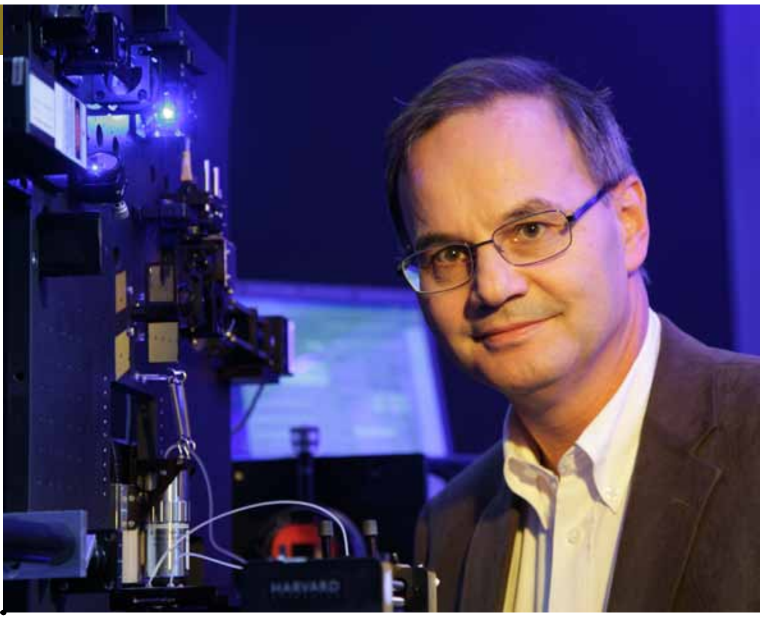
Nanostructure Optoelectronics

Prof. Dr. Artur Zrenner



The research activities of the nanostructure optoelectronics group are focused on the physics and technology of semiconductor nanostructures and on the development and application of advanced optical analytics.

Our work on semiconductor nanostructures is concentrated on the preparation and investigation of single quantum systems, their controlled manipulation and funtionalization on the level of single electrons, excitons, photons or spins. This research field falls into the area of solid-state based quantum information technology, in which the coherent control of single quantum systems is of fundamental importance.

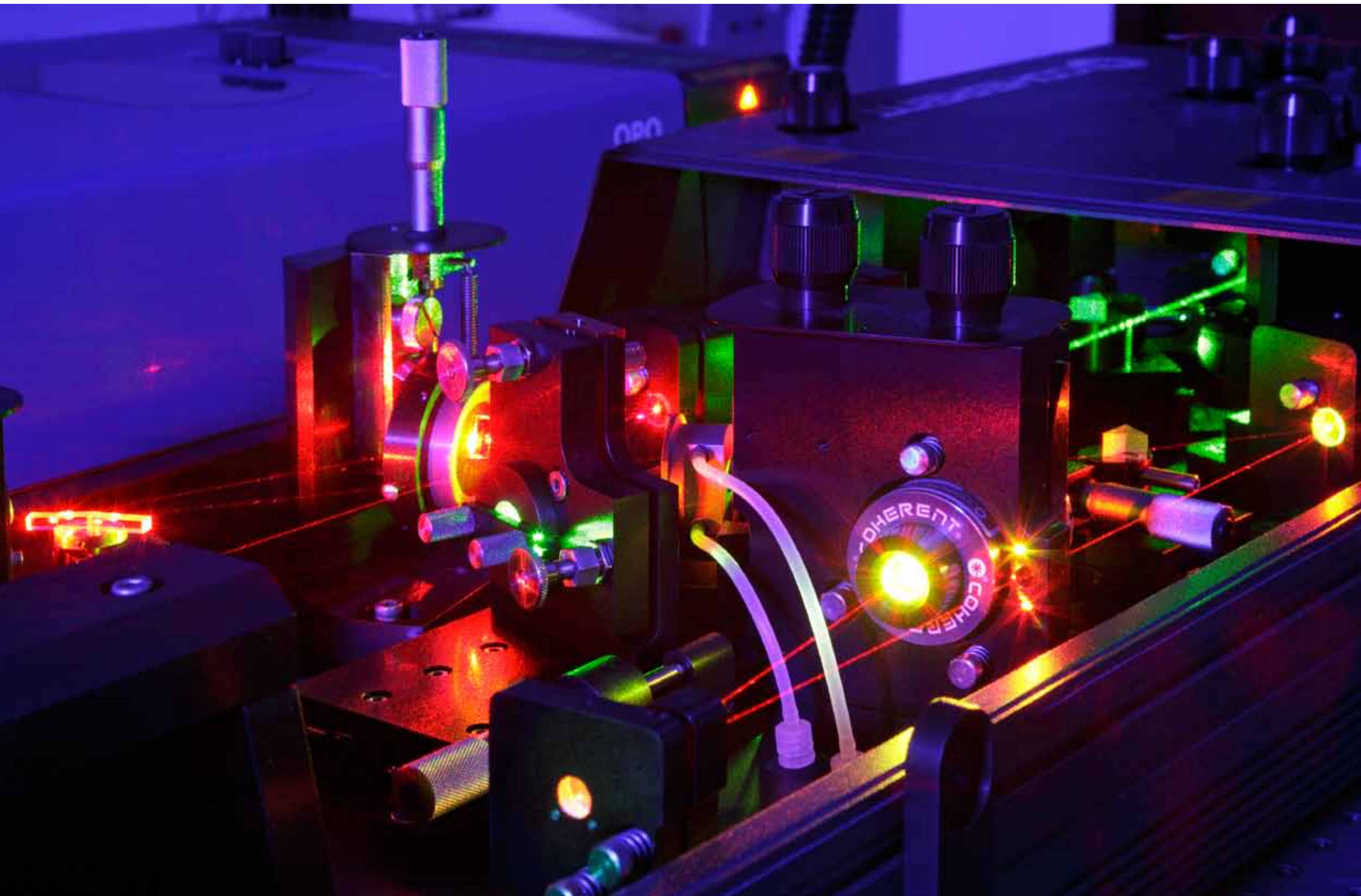
In the field of optical analytics we are focused on fs-nonlinear confocal microscopy and Raman imaging. Applied to semiconductors, periodically poled ferroelectrics, and chemical reactions in micro-cannels, those methods provide sub-µm spatial resolution and contrast mechanisms, which are inaccessible by linear optical microscopy.

Quantum information technology

Semiconductor quantum dots are artificial atoms contained in a host crystal. Their absorption and emission spectra appear as atomically sharp lines. By resonant optical excitation with a tunable laser system it is possible to generate or annihilate excitons (single electron-hole pairs) in the ground state of a quantum dot. With ps laserpulses it is possible to control excitons fast and efficiently in a defined way. Under those conditions, an exciton can be described as a quantum bit (qubit), which can be coherently manipulated in amplitude and phase.

For our experiments we use self-assembled InGaAs, CdSe, or GaN quantum dots, which have been grown by molecular beam epitaxy (MBE). From this material we produce single quantum dot photodiodes and photonic micro-resonators by electron beam lithography and wet-chemical or reactive ion etching.

Using photocurrent spectroscopy we have been able to demonstrate Rabi-oscillations of exciton qubits on ps time scales. A Rabi flop by means of an optical π-pulse corresponds to a basic qubit rotation in the context of quantum computing. Photocurrent detection revealed an optically triggered single electron turnstile effect, which is based on the transfer of coherent optical excitations into deterministic photocurrents. This concept allows for a quantitative readout of the occupancy of a single quantum system. For optical excitation with π-pulses a quantitative photocurrent I=fe is obseved, where f is the repetition frequency of the experiment and e is the elementary charge. In the focus of our current interests are further the coherent state preparation as a basis for efficient single photon emitters and the Ramsey-interference as a basis for the implementation of novel optoelectronic quantum gates. Our research activities in this area are funded by the BMBF "NanoQUIT" program. The ongoing activities are designed to contribute to the new fields of coherent optoelectronics and quantum communication.



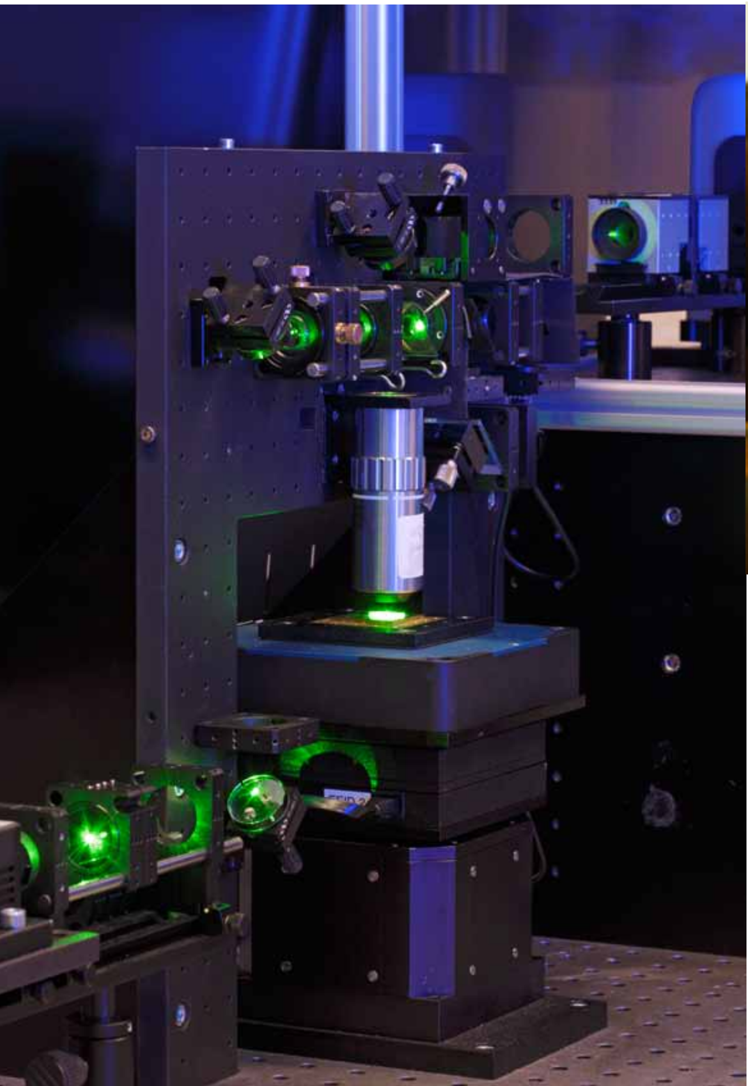
Modern Microscopy

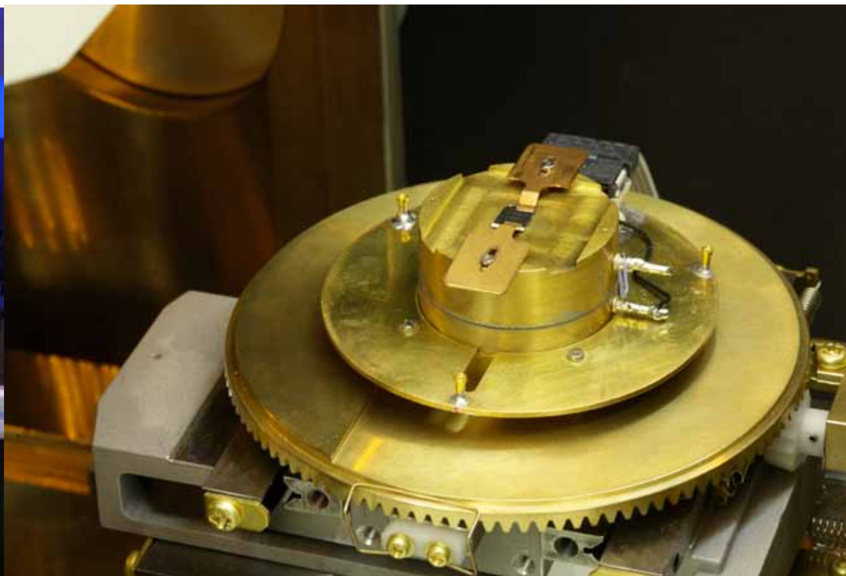
Linear confocal microscopy is a versatile tool for 3-dimensional image acquisition with sub-µm spatial resolution. Very often, however, linear scattering is not sensitive to the material properties or compositions of interest. Our research activities in the field of microscopy and optical analytics are therefore focused mainly on nonlinear techniques, which have the potential to provide new contrast mechanisms in many cases.

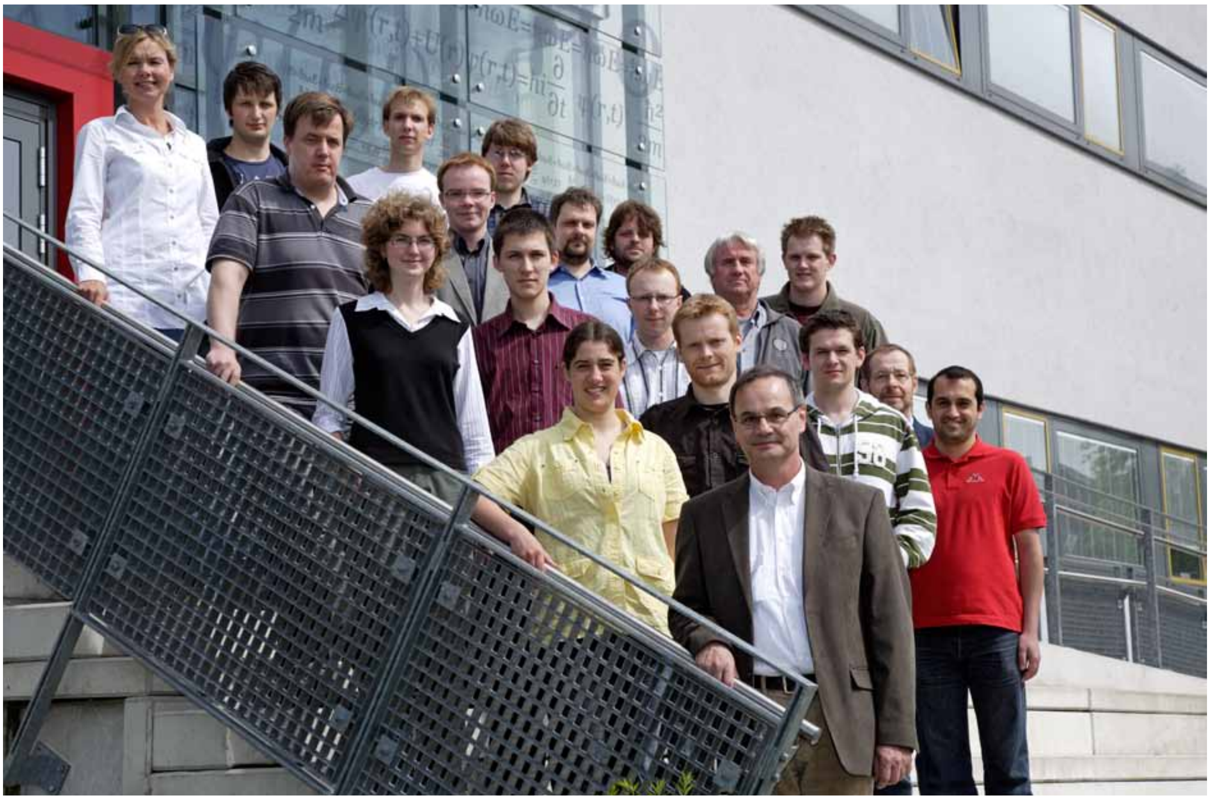
Second-harmonic imaging microscopy has been applied to obtain images of ferroelectric domain boundaries in periodically poled $LiNbO_3$ structures. Performed in a confocal mode, with a modern fs-laser source and single photon detectors, this method provides a tomography of the domain boundaries by scanning the specimen with respect to the fixed laser focus.

Raman imaging microscopy, also performed in a confocal mode, has been used for example to determine the strain distribution in pseudomorphic semiconductor nanostructures. Applied to ferroelectric domains, this method provides not only contrast to the domain boundaries, but also to the orientation of the individual domains. Because of its intrinsic sensitivity to the vibrational modes of molecular entities, Raman imaging is also a powerful tool to investigate the reaction kinetics in micro-channels under stationary flow conditions (funded by the Deutsche Forschungsgemeinschaft).

More recent, further activities within the group are focused on the microscopy and 2-photon absorption with entangled photons from parametric downconversion sources and on sub-nm-resolution length measurements by laser-interferometry.







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- Gerhard Berth
- Heike Degler
- Simon Gordon
- Thomas Hangleiter
- Klaus-Peter Hüsch
- Yves Alexander Leier
- Dirk Mantei
- Janik Mühe
- Peter Olenburger
- Wadim Quiring
- David Rasche
- Michael Rüsing
- Reiner Schneider
- Tobias Steinrücke
- Alex Widhalm
- Konstantin Weißgerber
- Volker Wiedemeier
- Janina Woitkowski
- Daria Wilke
- Artur Zrenner

Equipment

- Spatially resolved spectroscopy
- Raman spectroscopy
- Photon correlation spectroscopy
- fs nonlinear microscope
- Raman imaging
- ps/fs Lasersources
- Streak camera
- E-beam lithography
- Optical microscopy
- Rapid thermal annealing
- Spin coating
- Evaporation

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- 635 m^2 Offices
- 610 m^2 Laboratories
- 185 m^2 Lecture- and Meeting Rooms

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- Micromechanics
- Microoptics
- Microanalysis
- Nanotechnology
- Optical Analysis
- Optical Data Transmission and Bit Failure Analysis
- Lithography: e-beam and optical lithography
- Diffusion, Oxidation
- Rapid Thermal Processing (RTA/RTP)
- Evaporation and Sputtering
- Molecular Beam Epitaxy
- Laser scanning microscopy
- Low Pressure Chemical Vapor Depositon
- Plasma Enhanced CVD
- Reactive Ion Etching (RIE, PE)
- Advanced Silicon Etch (ICP-RIE)
- X-Ray Diffraction
- Scanning Electron Microscopy
- Atomic Force Microscopy
- Vacuum Scanning Tunneling Microscopy
- Transmission Electron Microscopy
- Confocal Microscopy
- Microprobe x-Ray Analysis
- Optical Nearfield Microscopy
- Ellipsometry
- Optical Spectroscopy
- Picosecond/Femtosecond Spectroscopy
- Infrared Spectroscopy
- UV Spectroscopy
- Residual Gas Analysis
- Polarimetry
- Raman Spectroscopy/Imaging
- Wafer Probe Station (110 GHz)
- Network Analyzer (110 GHz)
- Optical Spectrum Analyzer
- DC Parameter Analyzer
- Electroplating
- Ultrasonic Bonding
- Wafer Dicing

Directions

Fürstenallee Gebäude F
Neuhäuserstraße
Pader
Fürstenallee
Dubelohstraße
Fürstenweg
NBP
RailCab-Versuchsanlage
Wohn- und Gästepark
Mersinweg
Pohlweg
Liese-Dreyer-Weg
Broder-Carstensen-Weg
Studenten-
wohnheim
Peter-Hille-Weg
PLAZ
P1
P2
P3
P4
P5
P6
P7
P8
P9
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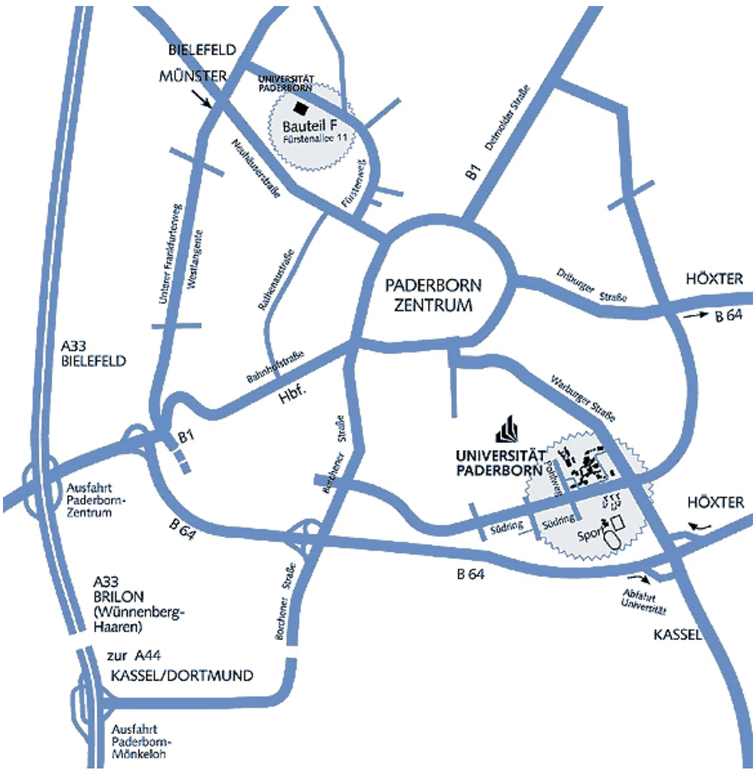
A
B
E
ME
H
ZD
V
IBZ
ST
C
D
AM
Auditorium
maximum
BI
Haupteingang
J
K
(im Bau)
S
Fanny-Nathan-Str.
iBFM
Verbindungshaus
zum Sport
zur Golfakademie
SP
auf dem
Sportgelände
NW
ZSL
NWL
Südring
Studentenwohnheim
Vogeliusweg
Warburger Straße
TVZ



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