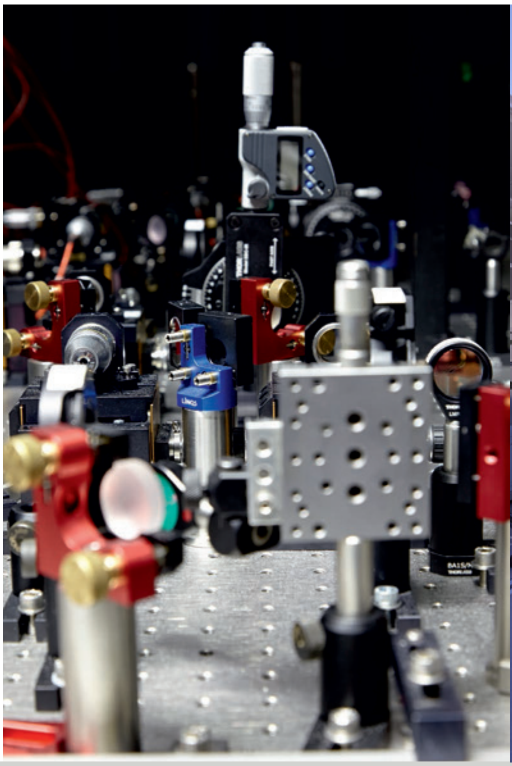
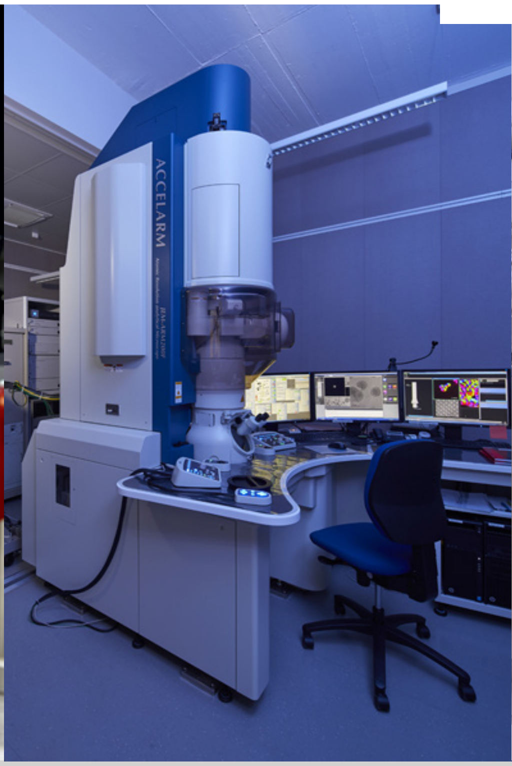
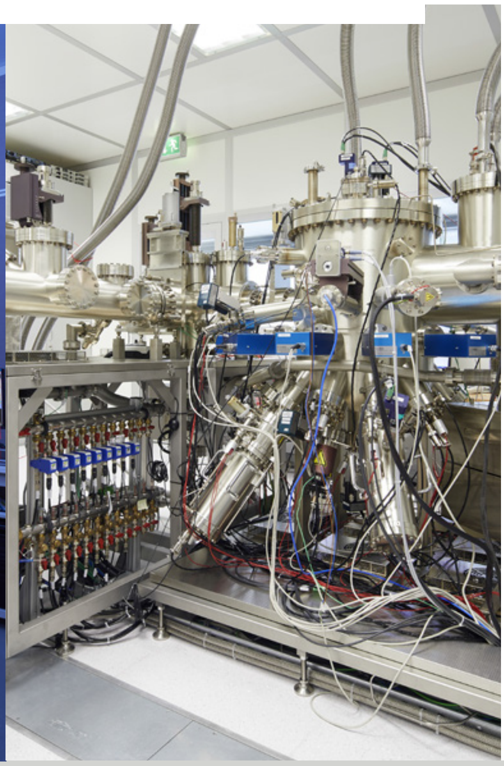
UNIVERSITÄT PADERBORN
Die Universität der Informationsgesellschaft







CeOPP

Center for Optoelectronics and Photonics Paderborn

Central Academic Facility of the University of Paderborn

Broschure 2017

Preface

The Paderborn University is well known as “The University for the Information Society”. Corporate Image, mission statement and all university activities aim towards this core competence. With its focus on the foundations and applications of intelligent technical systems, lightweight design with hybrid systems, optoelectronics/photonics and digital humanities the Paderborn University concentrates on the requirements of the information society. In accordance with this guiding principle the Paderborn University is a research 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 Paderborn University. Within the CeOPP, 20 groups from the departments of physics, chemistry, electrical engineering and information technology are currently collaborating in research and teaching. They develop novel devices and circuits based on innovative 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 perfect mixture of highly qualified young and experienced researchers, who guarantee constant progress and improvement. The Paderborn University will continue to promote this development and this field of research through further recruitments of qualified researchers and structural support.

From 2008 to March 2017, the DFG Research Training Group “Micro- and Nanostructures in Optoelectronics and Photonics” (GRK 1464) was a preeminent example of the joint and coordinated research and of the commitment to teach and support young academics in this field.

Since 2014, with the newly established DFG funded collaborative research center SFB TRR 142 on “Tailored nonlinear photonics: From fundamental concepts to functional structures”, top level research in the field of photonics and trendsetting quantum technologies are driving the future developments within this topical focus.

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

Prof. Dr. Birgit Riegraf,
Vice-President for Academic Affairs and Quality Management
of the University of Paderborn
July 2017

Table of Contents

About CeOPP

Since 1989 the University of Paderborn is constantly promoting research and development in tSince 1989 the Paderborn University 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 Paderborn University 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 be since then used for corporate research and development. 2008 marks the starting point of our joint research activities on “Micro- and Nanostructures in Optoelectronics and Photonics” within the framework of the DFG Research Training Group GRK 1464. In April 2014 we were able to start the new DFG-funded collaborative research center SFB TRR 142 on “Tailored nonlinear photonics” together with our colleges from the TU Dortmund University. With this pronounced focus on research in the field of novel optical technologies the CeOPP at the Paderborn University has become an important player in the field of optoelectronics, photonics, and emerging quantum technologies word-wide.

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 the most important key technologies for the next century. As a result of the structural development we have been able to establish two new Master programs in the areas of “Optoelectronics and Photonics” and “Materials Science”, which will both start in the winter term 2017/2018.

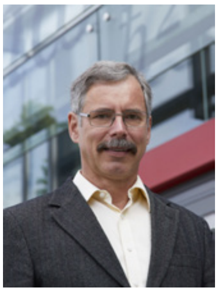
The mission of the CeOPP to promote the best possible professional qualification for the students is supplemented by the organization of the “Paderborn Photonics Lecture” about hot topics in the field, presented by distinguished external speakers and guest scientists.

By now, 20 designated members from the Paderborn University and five associated members join 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
July 2017

CeOPP Members




Professors

Prof. Dr. Donat As
Jun.-Prof. Dr. Tim Bartley
Prof. Dr. Jens Förstner
Prof. Dr. Wolf Gero Schmidt
Prof. Dr. Stefan Schumacher
Jun.-Prof. Dr. Polina Sharapova
Prof. Dr. Christine Silberhorn
Prof. Dr. Andreas Thiede
Prof. Thomas Zentgraf
Prof. Artur Zrenner

Professors

Prof. Dr. Ulrich Hilleringmann
Prof. Dr. Klaus Huber
Prof. Dr. Heinz-S. Kitzerow
Prof. Dr. Jörg Lindner
Prof. Dr. Cedrik Meier
Prof. Dr. Torsten Meier
Prof. Dr. Reinhold Noé
Prof. Dr. Dirk Reuter
Prof. Dr. Christoph Scheytt
Prof. Arno Schindlmayr


Academic Staff

Dr. Manfred Hammer (AG Förstner)

Staff

Dipl.-Math. Werner Sievers (AG Lindner)

Student Representatives

Lennart Lorz (AG Silberhorn)






Associated Members

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Prof. Dr. Simone Sanna

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Member of the CeOPP from 2016 to 2017
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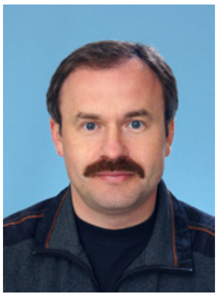
apl. Prof. Dr. Dmitri Yakovlev



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SFB/TRR 142
Tailored nonlinear photonics: From fundamental concepts to functional structures

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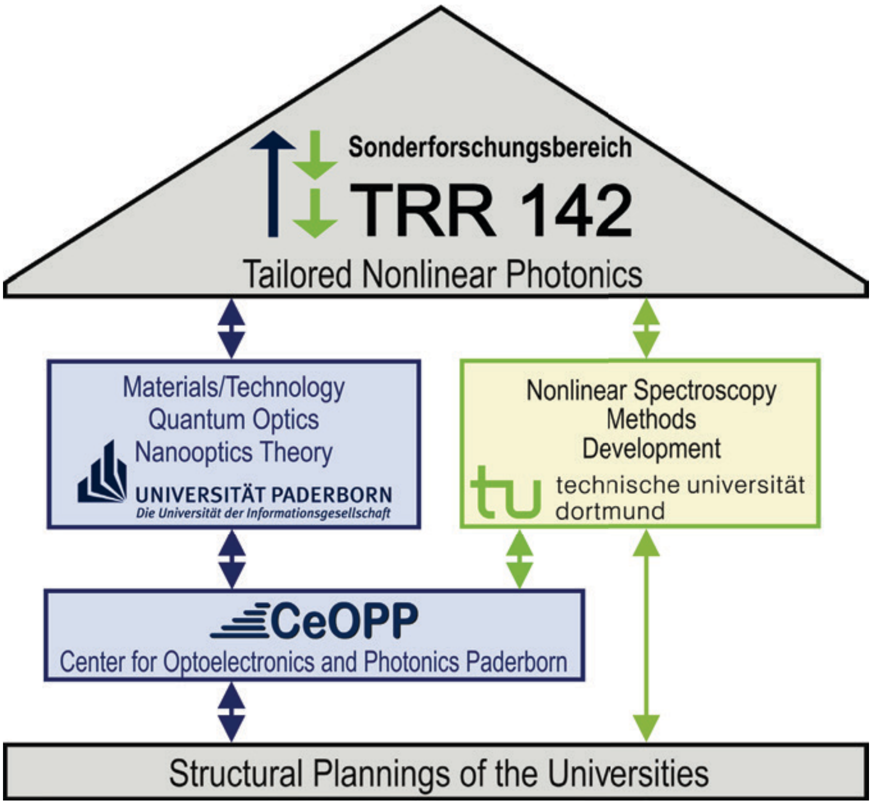
UNIVERSITÄT PADERBORN
Die Universität der Informationsgesellschaft
SFB TRR 142
technische universität dortmund

Principal investigators of the SFB/TRR142

Since 2014 the Collaborative Research Center/Transregio 142 funded by the DFG, started its work on the establishment of a new kind of tailored nonlinear photonics, which is driven by concepts from quantum optics, coherent optics, ultrafast optoelectronics, and solid state physics.
Organized as a comprehensive Transregio-program of the University of Paderborn and the Technical University of Dortmund it combines the core expertise of the University of Paderborn in photonic materials, technology, quantum optics, and theory with the competence of the TU Dortmund in nonlinear spectroscopy.

Networking the research at the two universities

The research activities of the TRR 142 and the CeOPP are in many respects interrelated since most of the principal investigators from the University of Paderborn are involved on both. The acceptance of researchers from the Technical University of Dortmund as associated members in the CeOPP enhances the strong interaction between the two universities resulting in the establishment of the collaborative research center TRR 142.



The research program of the TRR 142 brings together competence and resources from two universities. The researchers in Paderborn have a longstanding experience in the fields of nonlinear solid state materials, nanoscale fabrication technologies as well as engineering capabilities and theoretical support in both optoelectronics/photonics and computational material science. This is complemented by the expertise in the field of solid state ultrafast nonlinear spectroscopy and method development in Dortmund.

For the researchers within this network, it becomes possible to explore new materials and new physical concepts, to gain microscopic insights in established materials like $LiNbO_3$, and to design and technologically engineer new systems and devices for future applications.

Project areas and cooperation among the projects

The research program is entirely concentrated on the physics and applications of nonlinear light matter interactions. On the one hand, it is focused on the tailoring of the most important nonlinear interactions like frequency conversion processes based on nonlinear susceptibilities, the nonlinear control of the population, and nonlinear pulse propagation. On the other hand, it brings in new and promising concepts from quantum optics, coherent optics, and optoelectronics. These include nonlinear optical effects on the single photon level, the introduction of optically created virtual states for the control of transitions, and the optical or electrical control of nonlinearities in the coherent regime.

The research program of the TRR is structured into the following three project areas:

A: **Fundamentals**
B: **Materials**
C: **Functional structures**

These areas reflect the requirements for a coordinated long-term research program, which span the entire area from basic concepts of nonlinear photonics to functional structures on the basis of solid state materials.

Further information: **http://trr142.uni-paderborn.de**

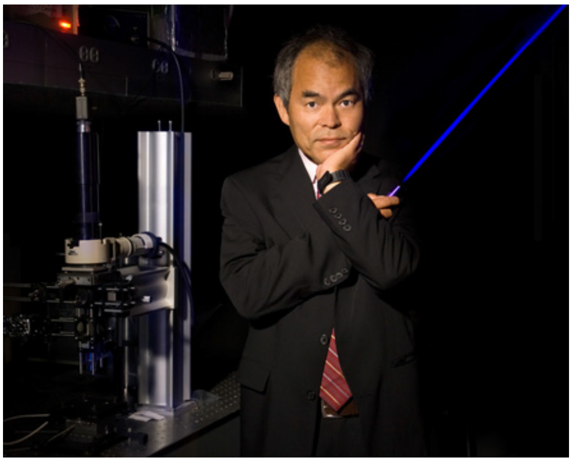
Celebration of the 10th anniversary of the CeOPP

Special lecture:
Professor Shuji Nakamura, laureate of the Nobel prize for Physics in 2014

Celebrating the 10th anniversary of the CeOPP, the TRR 142 and the GRK 1464 managed to invite Professor Nakamura as special guest for this event.

The event took place on November, 30th 2016 in the Auditorium Maximum of the University of Paderborn and was fully booked by the audience.
In his lecture with the title: "The invention of high efficient blue LEDs and future Solid State lighting", Professor Nakamura highlighted his invention and the role of high efficient blue LEDs which is regarded as a breakthrough in lighting technology.

In 2014 Professor Shuji Nakamura received the Nobel Prize together with Prof. Isamu Akasaki and Prof. Hiroshi Amano for the invention of high efficient blue LEDs. The three researchers engineered high-quality Gallium Nitride as a material for blue light emitting diodes, which are also the basis for white LEDs.
Professor Nakamura studied Electrical Engineering in Japan. Since 1999 he is Professor at the University of California Santa Barbara. In 2008, Prof. Nakamura, along with his collegues Prof. Dr. Steven DenBaars and Prof. Dr. James Speck, founded the company Soraa, which produces and markets high-end LEDs.



Prof. Shuji Nakamura, inventor of the blue LED, photo: Randall Lamb, UCSB

Reception in the city hall of Paderborn left to right: Prof. Dr. H. S. Kitzerow, Prof. Dr. A. Schindlmayr, Prof. Dr. A. Zrenner, Prof. Dr. C. Meier, Prof. Dr. h.c. Shuji Nakamura, Karsten Grabenstroer, Michael Dreier, Petra Tebbe, Prof. Dr. C. Silberhorn, Prof. Dr. C Scheytt, Andreas Keil. (Photo: Lisa Zölzer, Paderborn)

Special honors to CeOPP members

ERC Consolidator Grants for two CeOPP members

We are happy to congratulate two CeOPP members, Prof. Dr. Christine Silberhorn and Prof. Dr. Thomas Zentgraf who were awarded each with the ERC Consolidator Grant by the European Union research funding program Horizon 2020.
The two researchers are supported with 3.91 Million Euro within the next five years.

Prof. Dr. Christine Silberhorn is funded for her research on the topic of: “Quantum particles on programmable complex and reconfigurable networks.”
Prof. Dr. Thomas Zentgraf received the ERC Consolidator grant for his project with the title: “Functional extreme nonlinear nanomaterials.”

Priority Program “Electronic-Photonic Integrated Systems for Ultrafast Signal Processing“

The DFG will establish a new Priority Program “Electronic-Photonic Integrated Systems for Ultrafast Signal Processing“ which will start in 2018.

The initiative will be coordinated by Prof. Dr.-Ing. J. Christoph Scheytt from Heinz Nixdorf Institute and CeOPP. It aims to disrupt the fundamental speed limits of conventional electronic signal processing by nanophotonic/nanoelectronic technology and electronic-photonic system and circuit design. It is one of 17 newly installed Priority Programs in Germany.

Group III-nitrides for optoelectronics
Prof. Dr. Donat As

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Group III-Nitride forms a new class of semiconductors for modern applications in opto-electronics 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 inter-subband transitions (ISBT) or single photon emission are suggested. New quantum well infrared photodetectors (QWIPs), Quantum Cascade Lasers (QCL) and nonlinear effects 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 (FET)). The main research fields of the group, headed by 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.

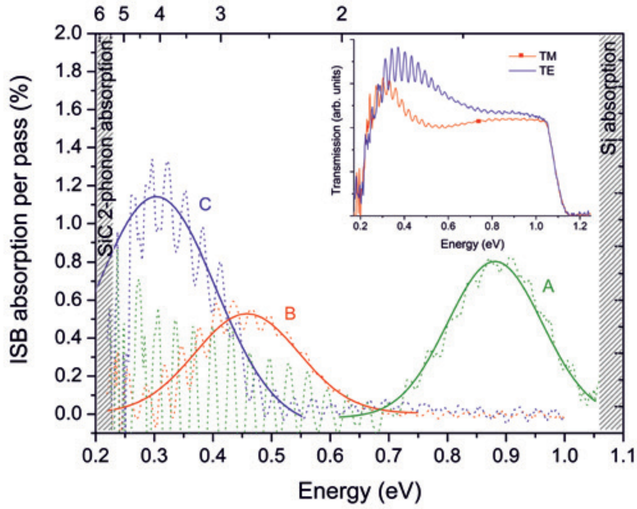
MBE growth of cubic Nitrides

Commercially available group III-nitrides have a hexagonal crystal symmetry, which leads to strong piezoelectric and spontaneous polarization fields. These strong “built-in” fields limit the performance of devices containing quantum wells or prevent the realization of field-effect transistors with enhancement characteristics. Polarization fields are absent in (001) oriented cubic III-nitrides.

We grow phase-pure cubic III-nitride epilayers, quantum wells (QW) and quantum dots (QD) by molecular beam epitaxy (MBE) and have demonstrated the 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.

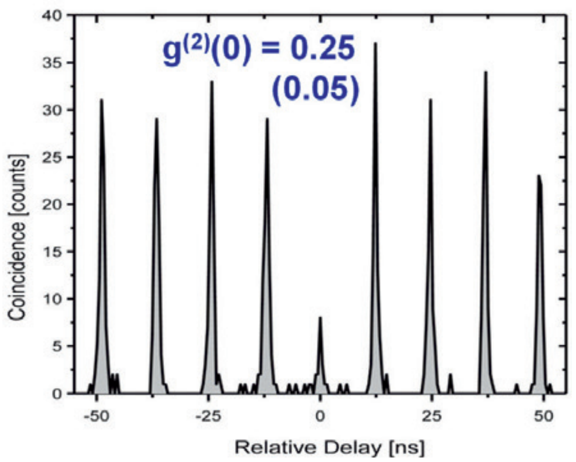
Optoelectronic applications

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 fast photo-detectors or modulators. Furthermore 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 absorption in cubic GaN/AlN quantum wells (QWs) have been observed in the near infrared spectral range and can be tuned over a wide spectral range from 1.4 µm (214 THz) to 63 µm (4.76 THz).



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

Within the collaborative research center and 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. We demonstrate single photon emission from individual c-GaN QDs with spectrally separated emission lines and fast decay times of several hundreds of picoseconds. In Fig. 2 the auto-correlation histogram of a single c-GaN QD emitting at 3.687 eV at 4 K is exemplary depicted. A $g^{(2)}(0)$ value of 0.25 can be estimated, but if the background contaminations are taken into account the value can be corrected to 0.05. Furthermore, single photon emission is measured at elevated temperatures of 100 K ($g^{(2)}(0) = 0.47$). The observed photon anti-bunching at low temperature is much better than for their self-assembled hexagonal counter-part. Our results indicate that c-GaN QDs are possible candidates for high-temperature operating UV single-photon sources with the possibility of integration into photonic structures.

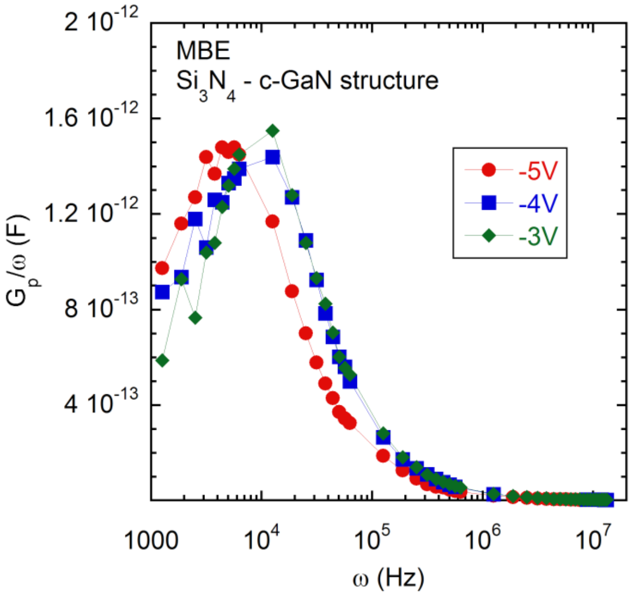


Autocorrelation histogram of a single c-GaN QD emitting at 3.687 eV at 4 K. The excitation power was 20 mW and the PL decay time is about 360 ps. The number in the bracket is the background corrected value of $g^{(2)}(0)$.

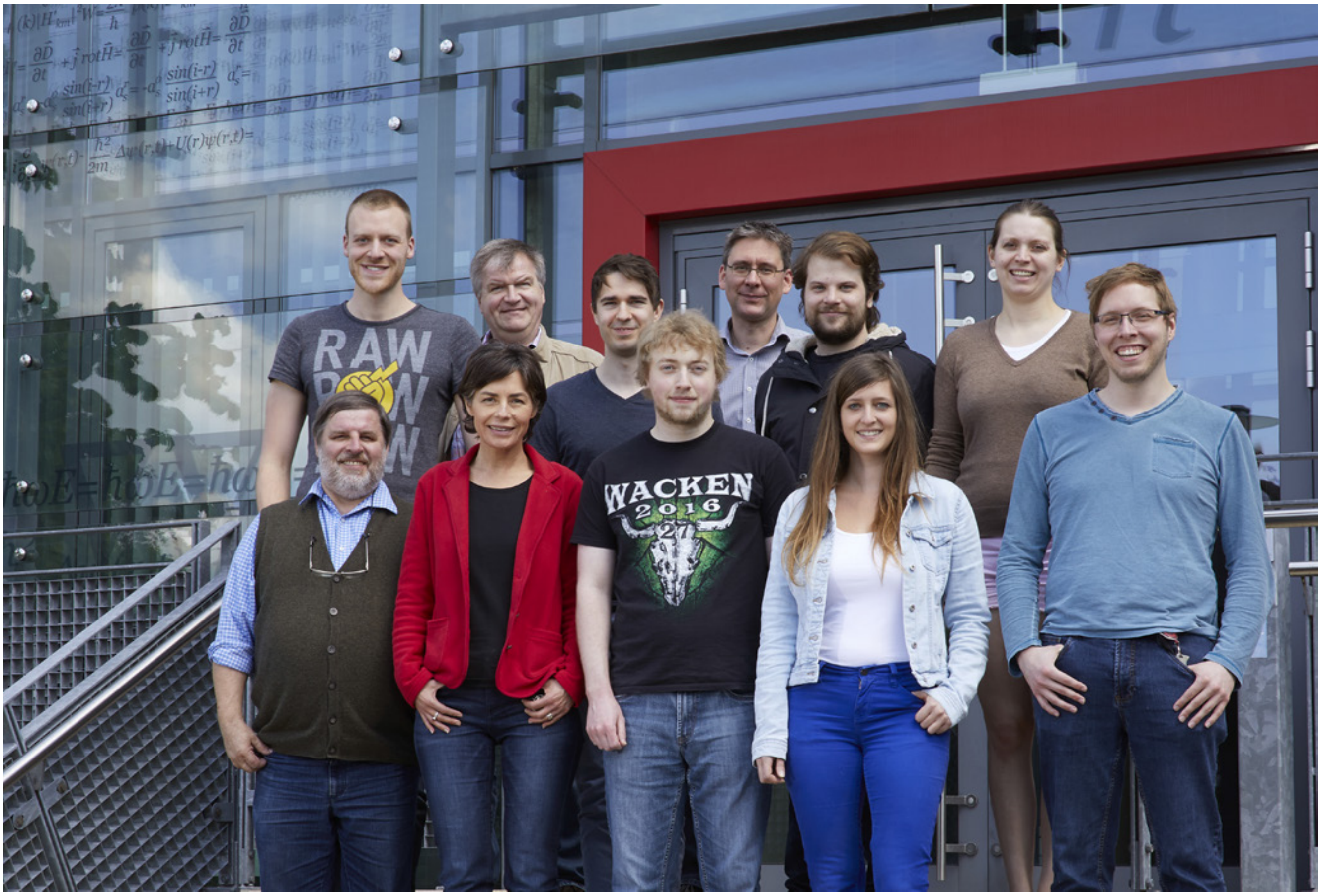
Electronic applications

AlGaN/GaN hetero-junction field-effect transistors (HFETs) are of major interest for the 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 normally-off FETs 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. However, the critical issue in the operation of the fabricated HFETs is the insufficient insulation of the gate contact. To improve the gate characteristics an insulating layer is required. Low interface trap density metal-insulator-semiconductor (MIS) interfaces are essential for high power and high frequency devices.

At the University of Paderborn a way was found to produce Si_3N_4 as the gate insulator in-situ directly inside the MBE chamber. A very sensitive technique (admittance spectroscopy) is used for characterizing insulator-semiconductor interface properties.



Admittance spectroscopic measure- ments Gp/ω versus the angular frequency ω for in-situ produced MIS structure.



Group Members

- M. Sc. Sarah Blumenthal
- M. Sc. Michael Deppe
- M. Sc. Tobias Wecker
- Anja Blank (team assistant)
- Prof. Dr. Donat J. As

Equipment

- Riber 32 Molecular Beam Epitaxy for Nitrides
- Reflection High Energy Electron Diffraction (RHEED)
- Quadrupol Mass Spectrometer (QMS)
- High Resolution X-ray Diffraction (HRXRD)
- Metal Evaporation System
- UV - Photoluminescence (2-300 K)
- Hall-Effect Apparatus (10-400 K)
- Electrical Parameter Analyzer
- Admittance spectroscopy
- Probe station for I-V and C-V
- Reflectometry

Mesoscopic quantum optics
Jun.-Prof. Dr. Tim Bartley

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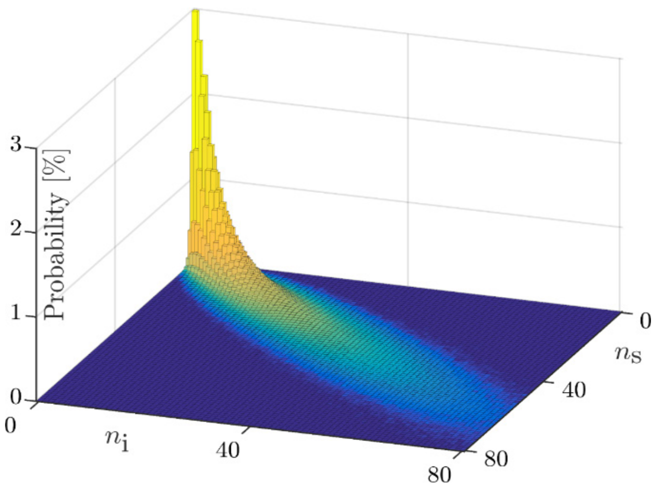
The Mesoscopic Quantum Optics (MQO) group uses light to investigate physical phenomena at scales that bridge the quantum and classical domains. Some of the most interesting and counter-intuitive consequences of quantum mechanics, for example superposition, wave-particle duality and nonlocality, are not part of our everyday experience of the world. We wish to find the scale limits on phenomena like these, and if and how they can be reached. Our route to building large quantum systems is to make big building blocks – large quantum states of light that can be combined to build even larger systems.

We use strong pumping of precisely engineered nonlinear interactions in waveguides to generate quantum optical states at mesoscopic energy scales combined with high-efficiency, low noise and high-speed superconducting detectors to enable the precise characterisation of these. Our ultimate aim is to unite these state-of-the-art techniques on a single monolithic platform, bringing together the advantages from each in a low-loss, high-stability and scalable architecture.

Introduction:

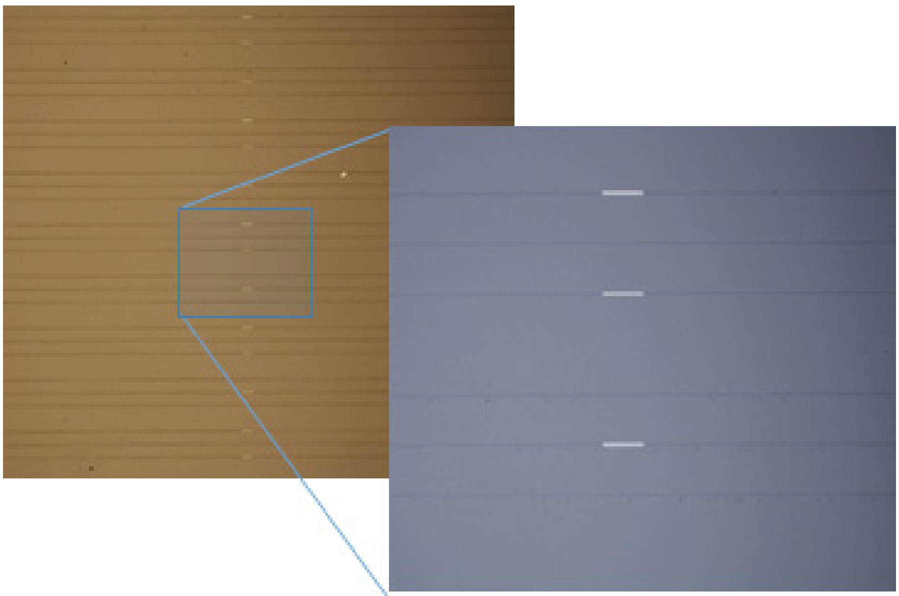
The MQO group investigates fundamental physics and develops quantum applications with mesoscopic-sized quantum states of light, all supported by relevant research on enabling technologies. Mesoscopic quantum optical states comprise 10s, 100s and 1000s of nonclassically-distributed photons. From a fundamental perspective, they can be used to explore quantum physics at energy scales that are visible to the eye, thereby exposing some of the highly counter-intuitive phenomena of quantum mechanics at a human scale. In addition, this scale is crucial for demonstrating a genuine quantum enhancement over classical schemes in many areas including metrology, computation and communication.



Joint photon number distribution arising from strongly-pumped parametric down conversion in a ppKTP waveguide.

Technology:

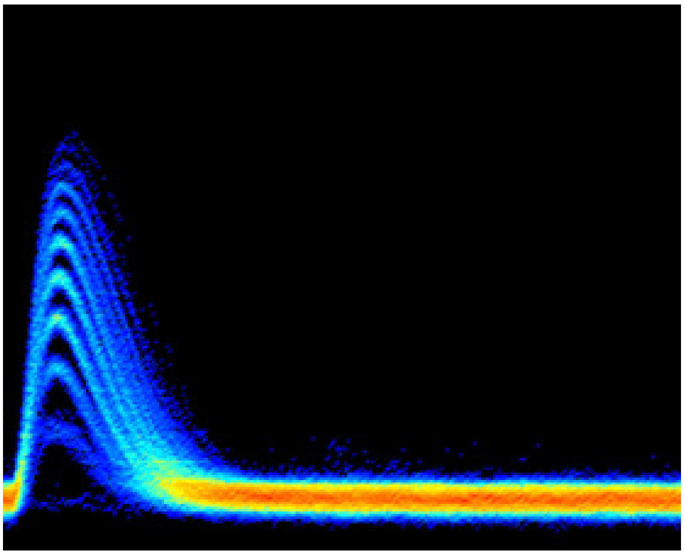
The three key elements of any quantum optics experiment are quantum light sources, state manipulation, and measurement. In the mesoscopic regime, this means generating lots of photons, manipulating them coherently, and measuring them efficiently. Almost all of these tasks are made easier by integrated optics, and lithium niobate is an ideal integration platform, benefiting from many years' development in the telecommunication industry. Our aim is to combine all the tools required for mesoscopic quantum optics experiments on a single device, to conduct experiments that go beyond what is possible using bulk optics. Specifically, we are depositing superconducting detectors directly onto waveguides in lithium niobate such that quantum states can be measured with high-efficiency on the same platform that they are generated and manipulated. Since these superconducting detectors must be cooled to temperatures approaching absolute zero, testing these devices involves developing cryogenically compatible packaging and coupling techniques ("pigtailing"). Not only are these useful in the quantum domain, but understanding how lithium niobate behaves at these cold temperatures is also of fundamental interest.



Deposition of thin-film tungsten on lithium niobate waveguides.

Fundamentals:

The role of quantum mechanics in large systems raises some very interesting questions. Can particle-like behaviour be seen in optical states containing 1000s of photons (analogous to wave-like behaviour of large molecules)? Can local realism be violated using large numbers of photons? And are there fundamental limits on the size, and therefore utility, of quantum systems, given the role of decoherence? We aim to answer fundamental questions like these to understand quantum mechanical effects as the scale approaches our everyday experience of the world. As well as being interesting in its own right, this is crucial to unlocking the huge potential of quantum mechanics for a variety of applications.

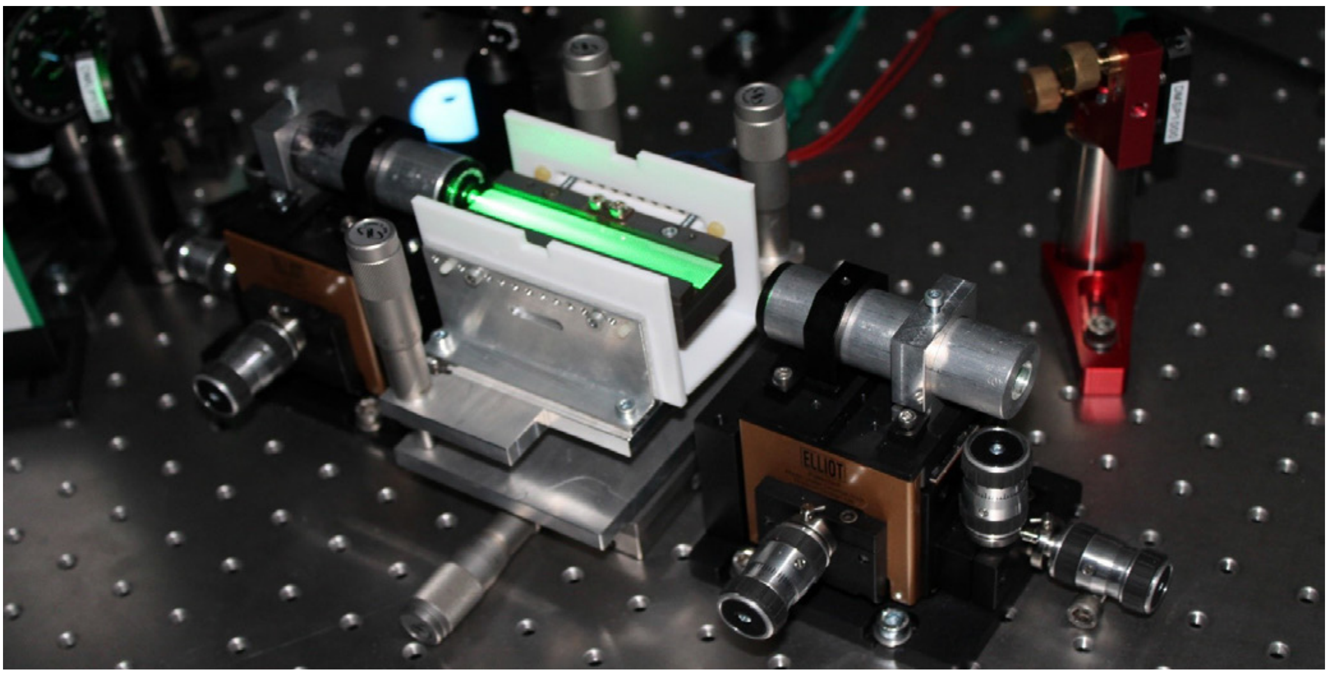


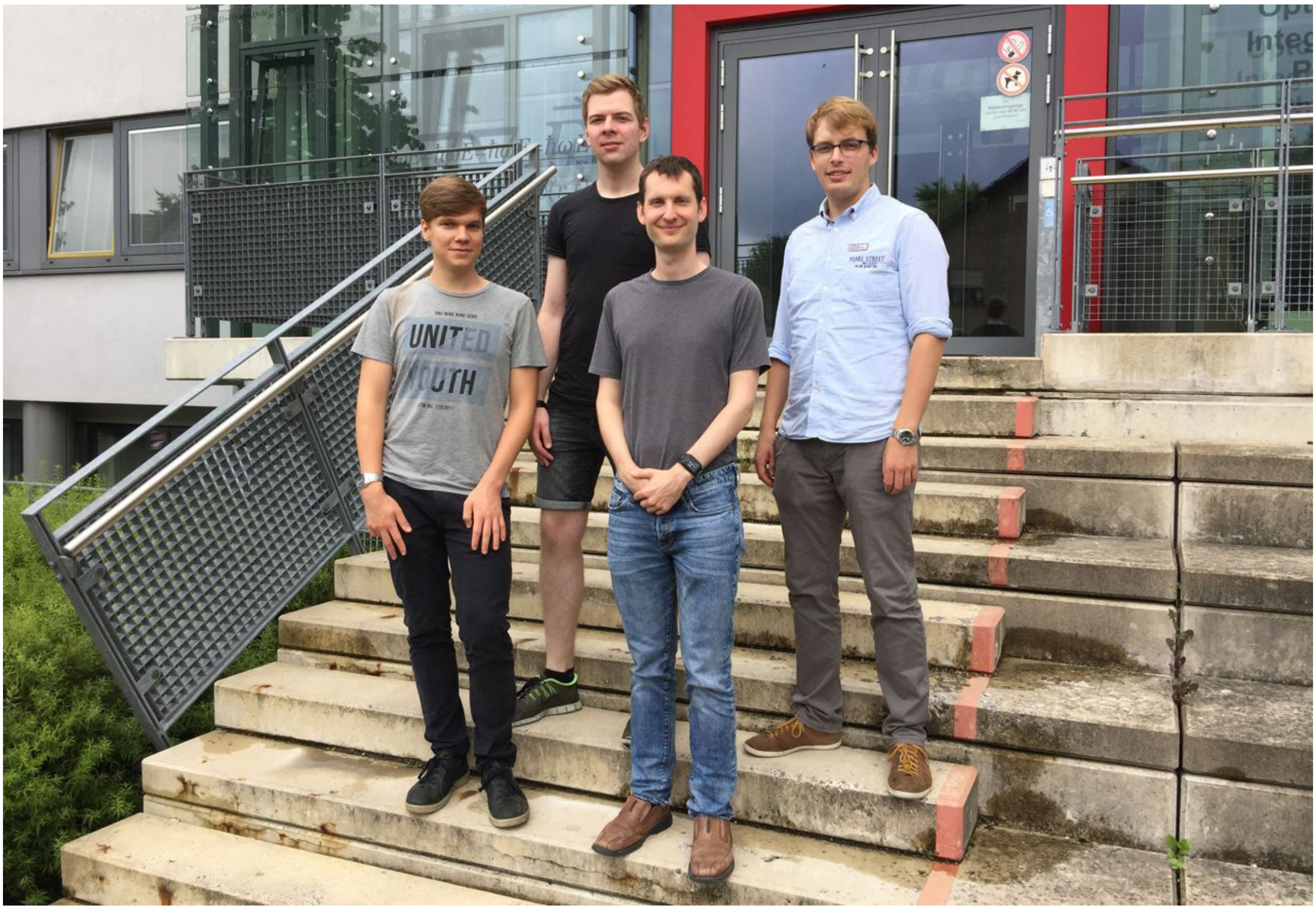
Trace from a transition edge sensor of a coherent state with a mean of four photons.

We have been able to push the boundaries of these questions with engineered parametric down-conversion in periodically-poled KTP waveguides to generate some of the largest quantum optical states. We have shown nonclassical phenomena in states up to 50 photons, and will continue to push this even further. Uncovering the rich structure of these states requires careful characterisation and development of new measurement strategies which can cope with such large numbers of photons.

Applications:

Phenomena such as superposition and entanglement do not appear in our everyday experience of the world, however exploiting these features can offer great potential in computation, communication and measurement. Key to unlocking these benefits is understanding how these phenomena can be made to persist at large scales, i.e. with many photons. Conventionally, one builds these systems up by concatenating sources of single photons, which can consume large amounts of resources. Our approach is to use bigger building blocks; that is, to start from states that are already contain many photons, which can directly be used to investigate quantum optics at large scales.





Group members:

- Moritz Bartnick
- Jan Phillipp Höpker
- Dr. Stephan Krapick
- Frederik Thiele
- Jun.-Prof. Dr. Tim J. Bartley

Equipment:

- Superconducting nanowire single-photon detectors
- Waveguide linear characterisation
- In-diffused nonlinear waveguides (ppKTP & ppLN)
- Ultrafast laser systems
- Cryogenic refrigerators

Theoretical Electrical Engineering
Prof. Dr. Jens Förstner

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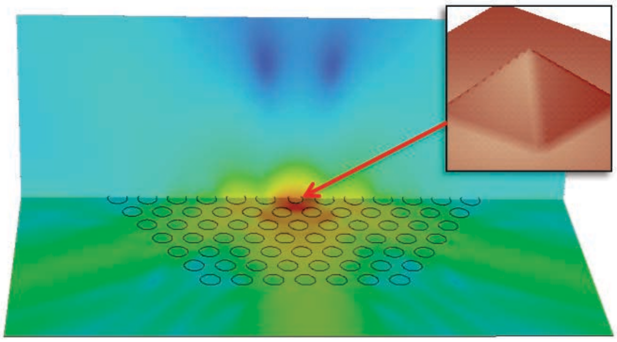
Since June 2013 Prof. Dr. Jens Förstner is head of the Theoretical Electrical Engineering group in Paderborn and new member of the CeOPP.
The group's research field covers a broad topical range from the simulation of light field propagation in photonic and plasmonic nanostructures to the microscopic modeling of optically nonlinear materials based on quantum mechanical theories. Within these topics, both the theoretical foundations and numerical methods are developed and applied.
Only this combination of advanced theories and numerical methods for the description of field evolution and nonlinear material dynamics allows the quantitative modeling of many interesting plasmonic and photonic nanostructures like solid state qubits in photonic resonators; nonlinear, active, and chiral metamaterials, sophisticated waveguides or tailored nanoantennas.

Semiconductor quantum dots embedded in photonic resonators

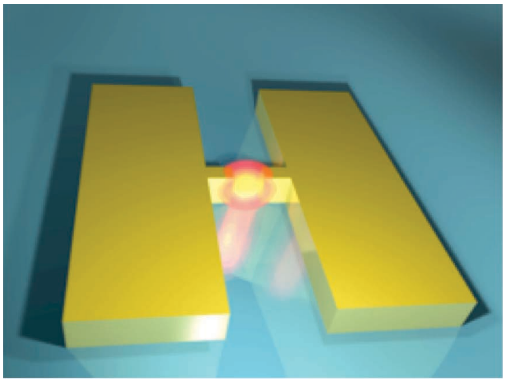
Photonic resonators facilitate the wave character of light using wave interference, multiple reflection and dispersion tailoring to build cages for photons, storing them for up to thousands of wave cycles. This is achieved by structuring dielectric materials on the scale of the wavelength. Two prominent optical resonators are photonic crystal cavities and microdisk resonators, which both are technologically feasible and provide very long capture times. The TET group managed to develop and apply powerful field simulation techniques based on the Finite Difference Time Domain (FDTD) method to these numerically challenging structures and achieved to quantitatively calculate and optimize the capturing of light fields even for complex multi-cavity configurations.



Quantum dot embedded in a photonic crystal slab cavity

Due to the long storage time of the photons and the related high field intensities, in a next step, it is very promising to place quantum mechanical resonators in such photonic resonators as one expects a highly increased interaction between light and matter. In solid states a good candidate are semiconductor quantum dots, in which charge carriers are quantum mechanically confined to very small scales (typically 5-50nm). These can be considered as stationary qubits coupled to the light field. Since the charge carriers also interact with the lattice vibrations of the solid state environment, i.e. phonons, and with other charge carriers, a complete microscopic theoretical description requires advanced many-particle quantum theories. The TET group has strong expertise in this area, especially in combining it with field simulation techniques, and was able to describe many fundamental effects like normal mode coupling in the strong regime, phonon-mediated Rabi-oscillations in single and coupled systems, and soliton-like propagation in quantum dot ensembles.

Nanoantennas



Theoretically proposed gold nanoantenna with maximized central field enhancement

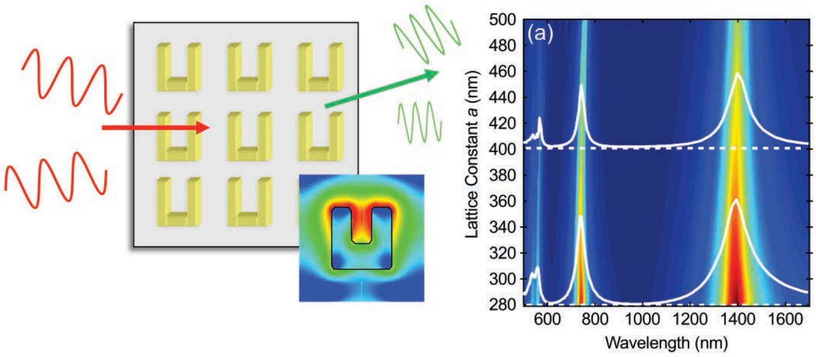
In metallic materials the high density of free electrons provides a plasma that can be optically excited. This leads to strong field enhancement and localization below the diffraction limit, i.e. below the vacuum wavelength scale. In plasmonic nanostructures this can be used to focus and steer light as required to build nanoscopic antennas. As the structures can be as small as the field penetration (skin depth), electromagnetic fields exist within the material - in contrast to macroscopic antennas. Also, nanoantennas are typically manufactured on a substrate. The theoretical modelling in the TET group takes these effects and the detailed near field interaction into account. Using automatic optimizing techniques it was possible to design novel gold nanoantennas (see picture), which provide better field enhancement than known configurations. Other properties like directivity have been improved as well, both with metallic and dielectric materials.

In addition to these linear effects, the TET group also develops microscopic theories to describe the nonlinear response of metals, e.g. based on the quantum mechanical Time-Domain Density Functional Theory (TD-DFT) or semiclassical hydrodynamical plasma models.

Nonlinear, active, and chiral metamaterials

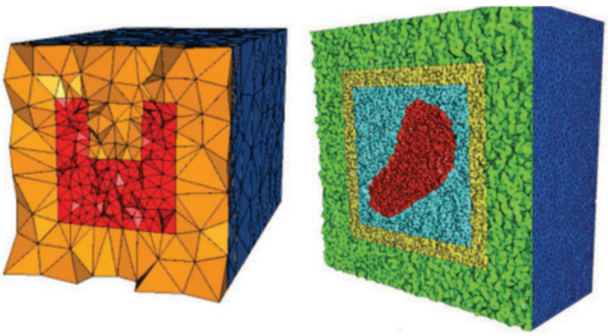
Considering ensembles of nanoparticles in regular or random arrangements, the light field instead of individual particles typically only sees the averaged material properties. By designing the particle shapes, orientations and arrangement it is possible to obtain effective properties that do not occur in natural materials, e.g. strong magnetic response at optical frequencies.

Several types of metamaterials have been considered in the TET group - e.g. chiral dichromatic metamaterials, in which the transmittivity depends strongly on the light polarization. Also, materials showing frequency conversion in the form of Second Harmonic Generation have been successfully simulated.

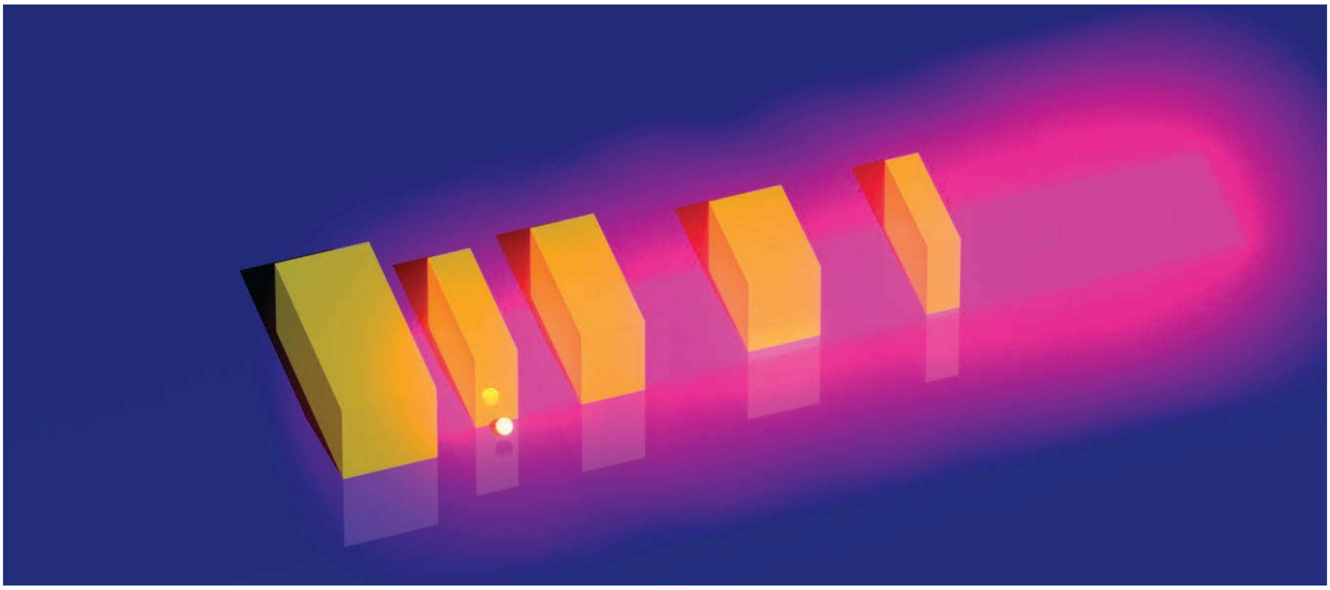


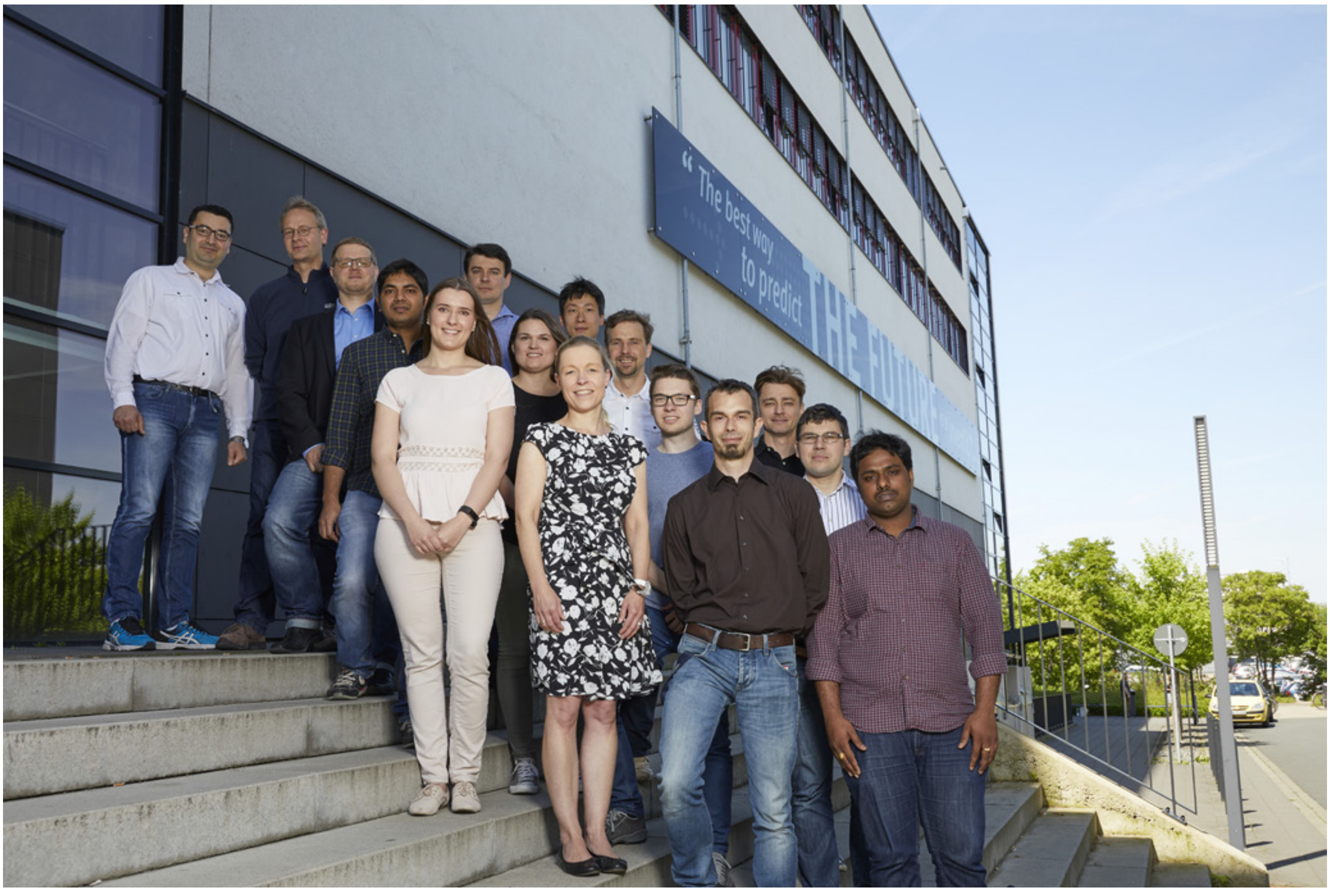
Second Harmonic Generation of an array of split-ring resonator nanoparticles

The simulation of such complex structures requires the development of novel numerical techniques like Maxwell solvers based on the Time-Domain Discontinuous Galerkin Method, which allows unstructured meshed and incorporation of microscopic nonlinearity models for the material dynamics. This opens up the possibility to simulate a wide range of geometries, from nanoparticles to interplanetary dust (see picture).



Numerical mesh of a nanoparticle (left) and interplanetary dust particle (right)





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- Dr. Manfred Hammer
- M. Sc. Peter Kölling
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- Dr. Viktor Myroshnychenko
- Dr. Denis Sievers
- Claudia Hagemeier (team assistant)
- Prof. Dr. Jens Förstner

Methods

- Time domain vectorial Maxwell solvers (Finite-Difference Time-Domain (FDTD), Discontinuous Galerkin, Boundary Element Method, Finite Integration Technique, Coupled Mode Theory)
- Nonlinear material theories (Semiconductor Bloch equations based on density matrix formalism, Dynamic Time Domain Density Functional Theory, Hydrodynamical Models, Quantum Trajectories)

Sensor Technology
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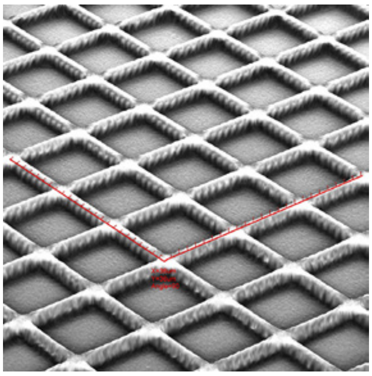
The research of the Sensor Technology group, funded in 1999, focuses on micro- and nanometer scale integrated circuits and sensors applying modern semiconductor processing.
In the area of automation technology new sensors or process applications are developed, e.g. passive RFID tags and readers with electronic ink displays, particle counters based on piezoelectric sensor arrays, algorithms for active noise control in tubes and integrated gas sensors for hydrogen and carbon oxide.
The current research emphasizes flexible field effect transistors with semiconducting nano-particles, thermoelectric generators for high temperature applications, dye sensitized solar cells, wave guide coupled optical microresonators for the telecommunication wavelength, micromechanics using electrothermal and electrostatic actors and self-sustaining wireless sensor networks.

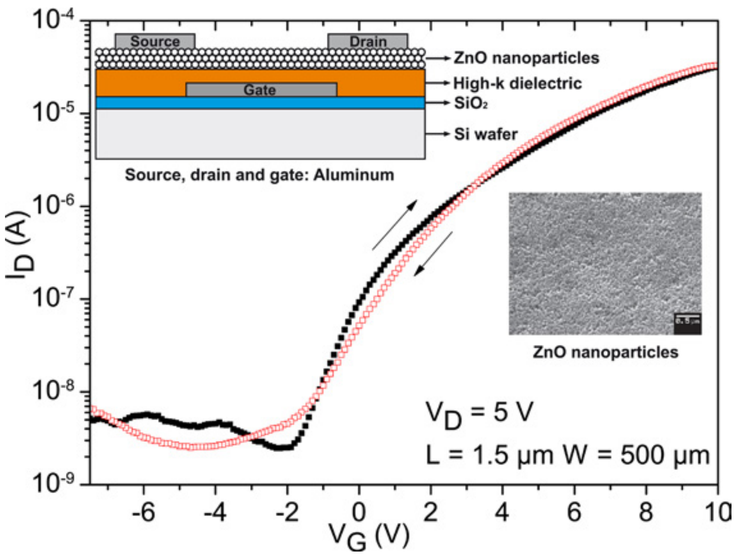
Flexible Electronics

Flexible electronics for low-cost/low-performance circuits are interesting for electronic devices on foil substrates. Here temperatures of over 200°C during the deposition must be avoided.



Grid structure for organic solar cells

Dye Sensitized Solar Cells (DSSC) are able to convert sunlight to electric energy, even under diffuse irradiation conditions. Cheap materials like titan dioxide with hibiscus dye allow a cost effective integration. To reduce the fabrication cost a metal grid is used instead of transparent conducting oxides (TCO). Here the size of the grid is smaller than the diffusion length of the charge carriers in the organic layer to reduce recombination losses. Pulsed UV radiation is used instead of sintering to enhance the layer quality. Currently the long term stability and the enhancement of the efficiency are explored.

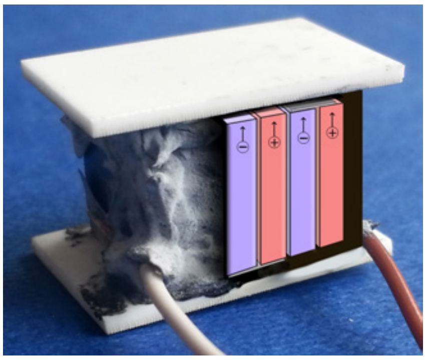


Nanoparticle field effect transistor with associated input characteristics

Field effect transistors with zinc oxide (ZnO) or silicon (Si) nanoparticles are of interests for flexible circuit applications. Compared to organic electronics, nanoparticle FET's provide some advantages due to their superior stability, charge carrier mobility and supplying voltages. Different structures are used to investigate the transistor performance, from thin-film transistors to single particle transistors. The integration process of single particle transistors is based on the side-wall etch-back technique, in which a metal trench is integrated, and then filled with nanoparticles forming the transistor channel. Nanoparticle FET's with field effect mobility of 0.2 cm^2/Vs have been realized. Additionally, aiming low-cost application and high-throughput manufacturing process in flexible substrates, simple and cost efficient techniques as spin-coating and spray-coating have been used, as well as low temperature processes. Current research focuses on contact potential engineering, process stability on flexible substrate and reliability of the integrated devices.

Thermoelectric Generators

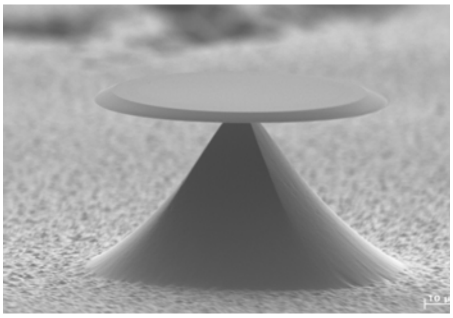
Fossil energy carriers become more and more expensive. Due to thermal losses a large amount of the energy is wasted to the ambient environment. With thermoelectric generators (TEG) some energy can be recovered using the material dependent Seebeck effect. Currently available TEGs are limited to about 300°C. In a BMBF funded project thermoelectric generators for temperatures up to 850°C are invented. A silicon based high temperature TEG was successfully integrated with titanium silicide contacts which provide a low contact resistivity and a high thermal stability. With iron silicide or zinc oxide thermoelectric generators can be fabricated using sintering processes which results in a higher efficiency for high temperatures. A possible application is the integration into the exhaust system of motor vehicles or power plants.



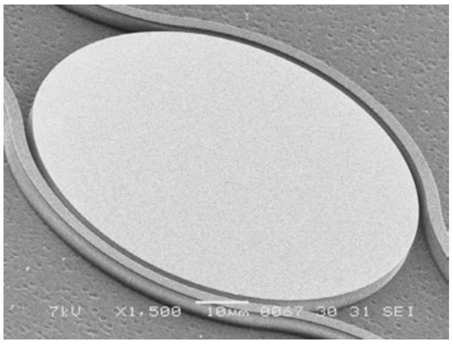
Thermoelectric generator with titan silicide contacts

Integrated Optics on Silicon

Silicon based optoelectronics are of great interest for mass fabrication to combine CMOS circuits with integrated optical components on a single chip using standard semiconductor processing. Microresonators can provide applications in communication and sensor technology. The narrow line width of the resonance frequency enables the realization of narrow line width filters and sensors with detection rates down to single molecules. The electromagnetic wave is guided near the surface by repeated internal total reflection at the boundary of the microdisk which forms a whispering gallery mode. Due to radiation loss the quality factor strongly depends on the surface roughness of the microresonator structure. Using optimized deposition and etching processes microresonators with a quality factor up to $1.3 \cdot 10^5$ are realized. Microresonators with integrated emitters are promising structures for integrated lasers with a low threshold power. Here erbium can be used as emitter for the telecommunication wavelength at 1550 nm. Excitation of the resonator can be realized by evanescent field coupling of integrated waveguides. Here the distance between waveguide and resonator has an influence to the coupling strength between waveguide and resonator. For a variable coupling the waveguide can be integrated on a micromechanic actor to change the distance between waveguide and resonator.



Silicon oxinitride microresonator on a silicon substrate



Waveguide coupled microresonator based on silicon oxinitride

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- Dipl.-Ing. Marcel Schönhoff
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- Emma Lose (apprentice)
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- Sebastian Lappe (technician)
- Dipl.-Ing. Dmitry Petrov (technician)
- Sabine Schleghuber (team assistant)
- Prof. Dr.-Ing. Ulrich Hilleringmann

Equipment

- Atomic Force Microscopy
- Lithography (0.8 µm)
- Dry Etching (RIE, ICP, PE)
- Ellipsometry
- LPCVD (SiO_2, Si_3N_4, Poly-Si)
- PECVD
- Sputtering/Evaporation
- Oxidation/Diffusion/Sintering
- Parameter/Network Analyser
- Rapid Thermal Annealing
- Wafer Prober

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

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

Static and dynamic light scattering (LS), small angle neutron scattering (SANS) and small angle X-ray scattering (SAXS) are used to investigate these structural transformations, whereby time-resolved measurements with all of these methods are applied as a new and powerful tool.

1) Nucleation and growth of inorganic particles

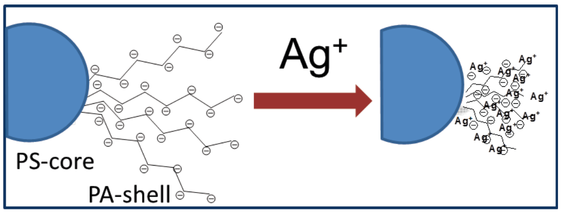
Nucleation and growth of particles are essential features of the formation of stable and metastable solid phases in a bottom-up approach. These processes are of fundamental importance, bearing considerable relevance to countless processes in nature and industry. Typical examples are the generation of nanoparticles of noble metals, the formation of high performance materials from supersaturated solutions of calcium carbonate and phosphate in nature or the development of highly porous materials like metal organic frameworks (MOF) in order to store hydrogen or to act as catalysts. By applying new techniques in time-resolved LS and SAXS, we succeeded to shed light on the mechanism of amorphous $CaCO_3$ formation and are currently investigating the formation of silica nanoparticles and zinc imidazolate frameworks. Development and application of new kinetic models to describe time-resolved scattering data is expected to reveal nucleation and growth mechanisms for the formation of nanoparticles.

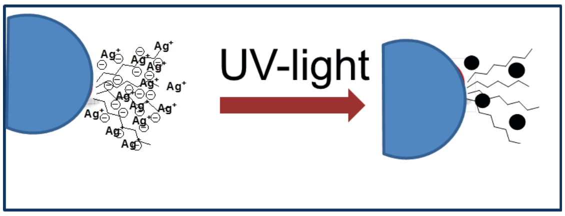
2) Self-assembly of low molecular weight gelators and biopolymers

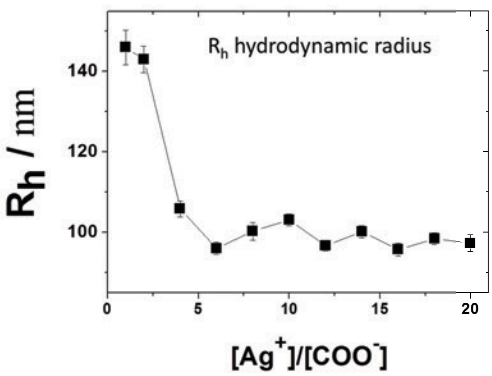
Numerous synthetic, low molecular weight compounds like organic azo-dyestuffes form fiber-like aggregates in solution in close analogy to proteins of living cells. The underlying processes can be regarded as physical polymerisations with a structural diversity, which is just as large as the complexity observed in macromolecular chemistry. In order to reveal general principles on this self-assembly, several low molecular weight systems like anionic azo-dyestuffs have been selected for a detailed investigation with time resolved LS. These systems shall be compared with the behaviour of Aβ-amyloid responsible for the Alzheimer disease and with proteins participating in the cytoskeleton. It is the final goal to unravel aggregation mechanisms and to develop tools to control aggregate size, size distribution and aggregate morphology.

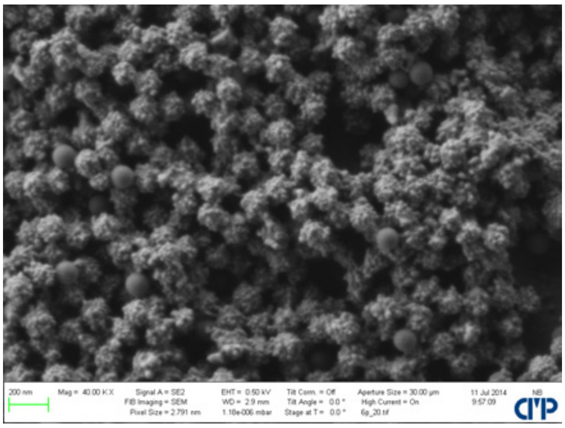
3) Conformational changes of polyelectrolyte chains induced with specifically interacting metal cations

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 dimensions 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 main group metal cations like 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 enable us to select any intermediate state along this shrinking process and to analyse structural details of such intermediates by combined static and dynamic LS and SAXS and SANS. A particularly interesting system under current consideration is the solution of Ag^{+}-salts in the presence of long chain polyacrylates, where the anionic chains serve as UV-assisted reducing agent and as host for the thus prepared Ag-nanoparticles. Based on this knowledge more complex core-shell colloids shall be designed for applications in photonics.



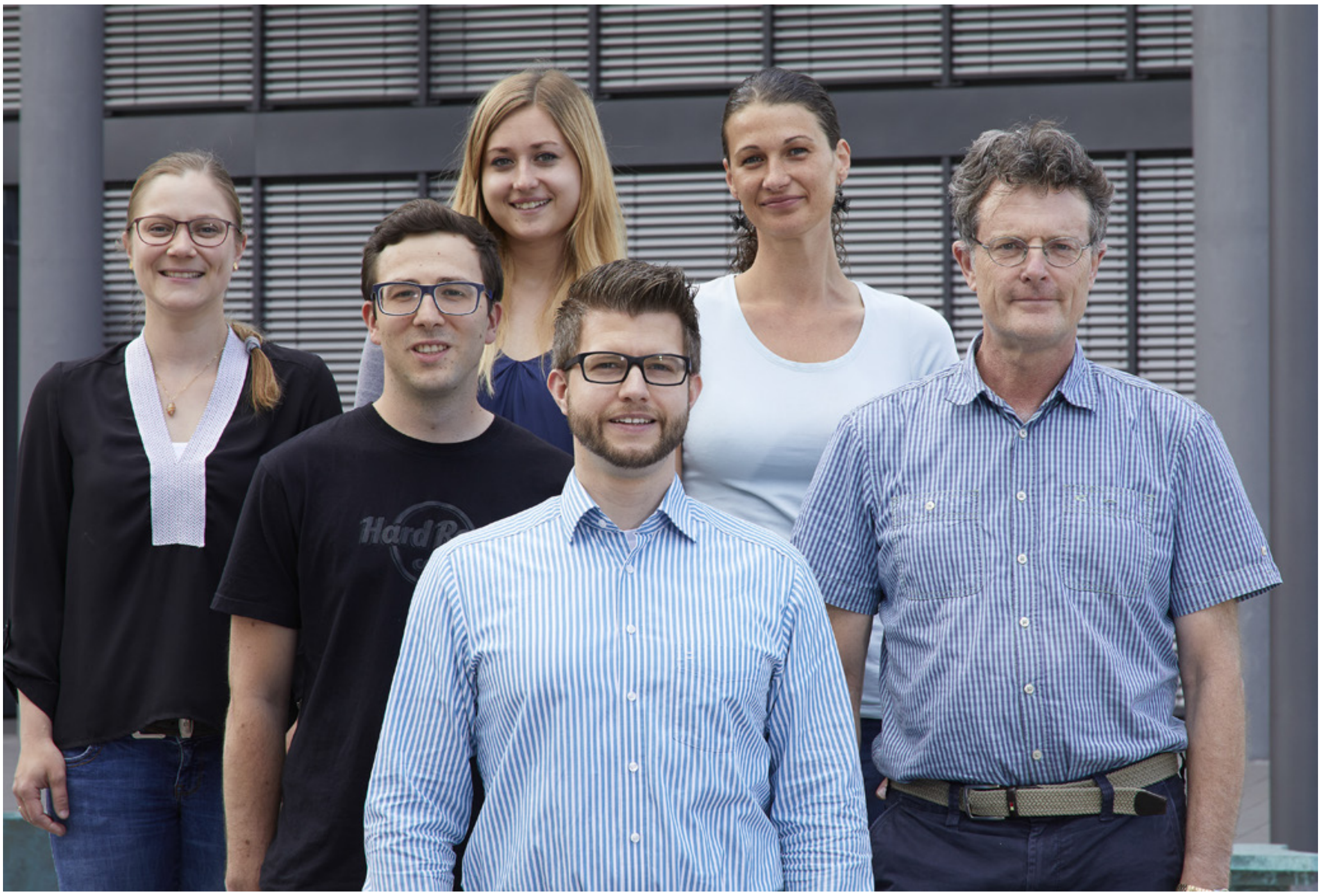






4) Organization in complex colloid suspensions

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 renders them a class of compounds which is highly suitable to investigate interaction patterns of proteins and to tune organization of colloids into highly ordered assemblies. We currently focus on the design of new colloidal systems capable of forming crystal-like assemblies while at the same time bearing specific optical properties. To this end, we currently prepare complex core-shell (polystyrene-polyacrylate) colloids, which are designed to be covered in a controlled way with Ag-nanoparticles. The final aim with complex colloids is to accomplish - in close collaboration with the Physics Department - particles with strong optical magnetism.



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- Dipl.-Ing. Susanne Keuker-Baumann (technician)
- Isabella Koralewicz (team assistant)
- Prof. Dr. Klaus Huber

Equipment

- ALV/CGS-3/MD-B Multidetection Laser Light Scattering Goniometer System for time resolved experiments
- ALV 5000E CGS for static and dynamic light scattering
- Home built static light scattering instrument for time resolved experiments
- High temperature GPC Alliance 2000
- Differential refractometers

Liquid Crystals
Prof. Dr. Heinz Kitzerow

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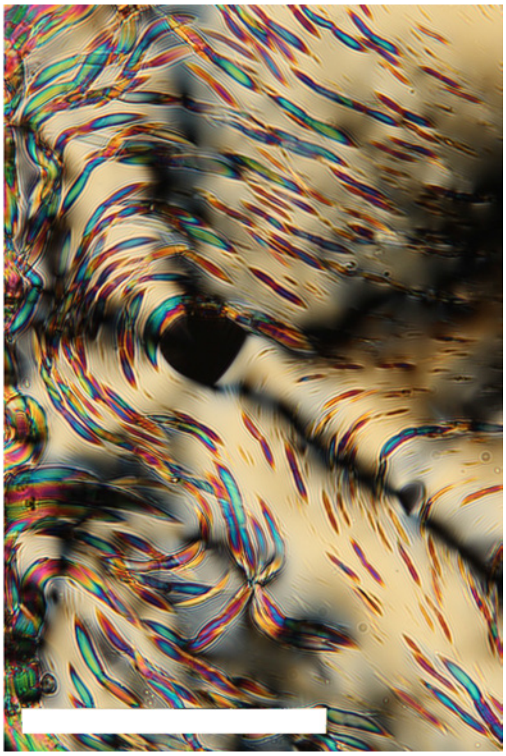
Liquid crystals are ordered fluids that play an important role in living organisms and in information technology. Flat TV and computer screens make use of thermotropic calamitic liquid crystals, which consist of rod-like molecules that are preferentially parallel aligned. This orientational order leads 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.

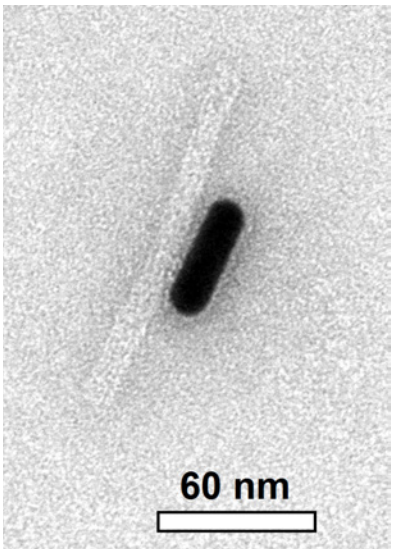
Electro-optics of polymer composites and nanoparticle dispersions

Combining the anisotropic optical properties of liquid crystals (LCs) with the mechanical properties of polymers has a large potential for possible applications. Flexible displays, optical polarizing or compensating filters, switchable holograms and optical storage are just a few examples of emerging technologies. Currently, we are working on polymer-stabilized blue phases, which are promising materials for a new generation of liquid crystal displays (LCDs). They exhibit fast switching, high contrast and easy fabrication. The benefits of the underlying optical Kerr effect have been known for a long time, but only the combination with a polymer network enabled enhancing the temperature range of the appearance of LC blue phases to values that are technically needed.



Light scattering setup for basic investigations on blue phases [Dr. Jürgen Schmidtke]

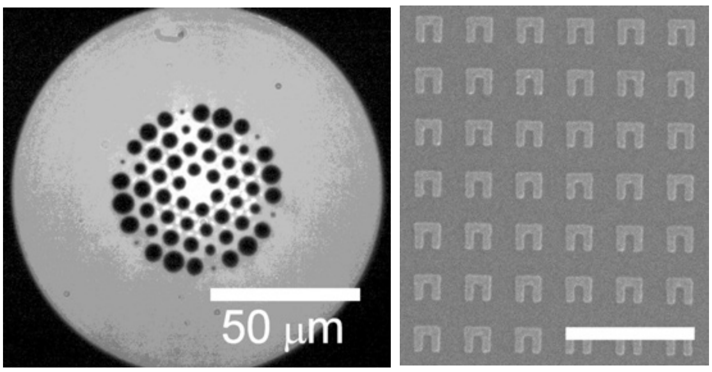
Dispersion of nanoparticles in ordered fluids can also alter and hopefully enhance the electro-optic performance of LCs, considerably. Our studies include the dispersion of metal-, luminescent semiconductor-, dielectric and ferroelectric particles in LCs. Confocal microscopy, X-ray diffraction and electro-optic studies indicate that nanoparticles can alter the alignment, the order parameter and the electro-optic switching behaviour. In collaboration with Prof. Tim Liedl at LMU Munich, we study the behavior of more complex DNA nanostructures (fabricated by the DNA origami approach) which are embedded in liquid crystals.



Gold nanorod on a DNA origami nanostructure [TEM, recorded by Bingru Zhang]. Right: Cromoglycate needles induced by DNA nidi decorate a LC [polarisation-optical micrograph, scale bar: 200 µm].

Tunable micro- and nanostructures

Photonic crystal fibers contain an array of holes extending along the fiber axis and are exceptionally versatile. They can guide optical signals very efficiently, like conventional light guiding fibres applied in information technology. Infiltration with a LC can turn micro-structured fibers into controllable, integrated color-, intensity- or polarization filters. Metal nanostructures of sub-wavelength size can even yield effective material parameters that are not found in nature. Tuneable metamaterials are obtained if plasmonic structures of this

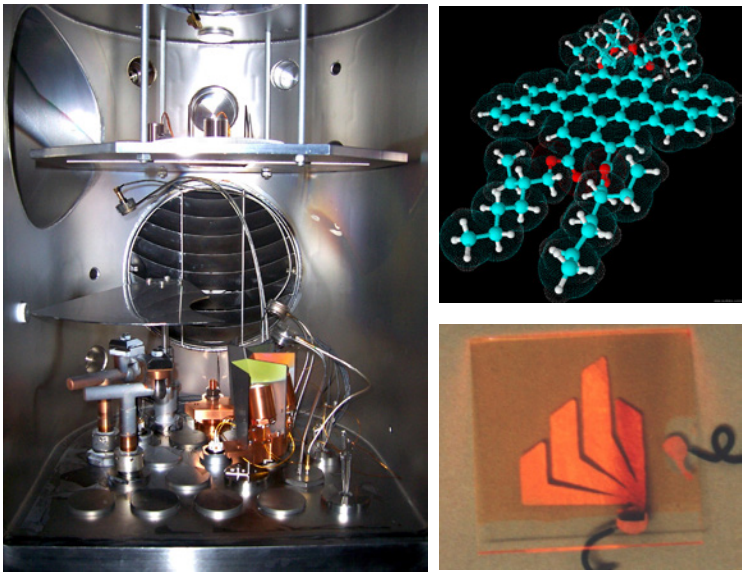


Micro- and nanostructure, which were filled or covered with a liquid crystal. Left: photonic crystal fiber, right: array of plasmonic split ring resonators (bar: 1 µm).

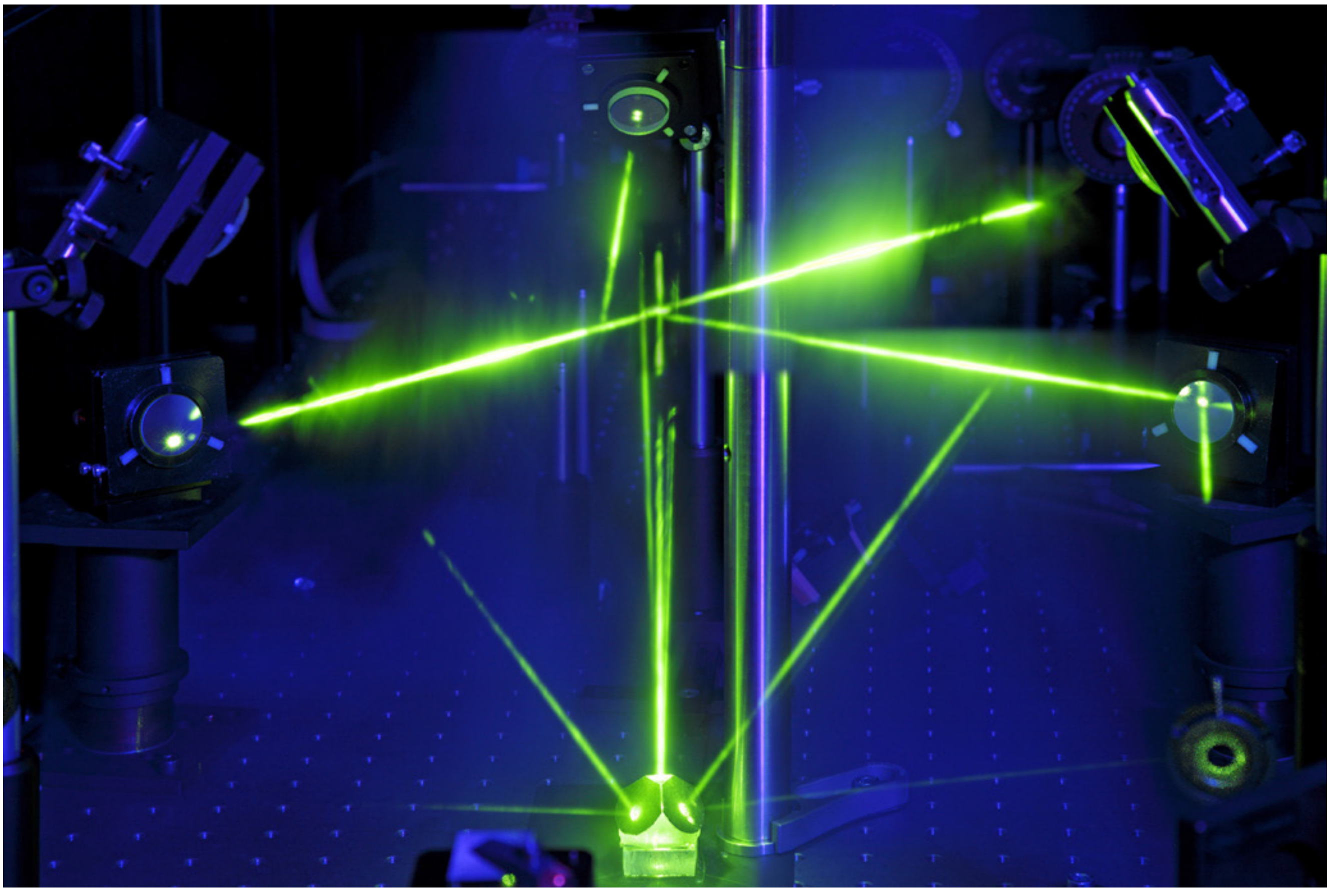
kind are embedded in a LC. Their transmission spectra can be controlled by thermal addressing, by applying voltages or by non-linear optical effects, such as the “colossal optical nonlinearity”, an extremely large optical Kerr effect.

Organic light sources

Many optical applications require small and highly efficient optical light sources. Cholesteric LCs show an intrinsic periodic helical structure, which can replace a laser resonator. Dr. Jürgen Schmidtke works very successfully on fabricating and characterizing tuneable lasers based on polymer and low molar mass cholesteric LCs. Other classes of LCs, smectic and columnar liquid crystals, can act as organic semiconductors with an unusually high charge carrier mobility. Their electrolumimescent application requires sophisticated nanostructures composed ultrathin multilayers. Unlike luminescent polymers, LCs are capable of emitting polarized light. Their performance can be enhanced by embedding in a microresonator.



High vacuum chamber for fabricating ultrathin organic layers by physical vapor deposition, structure of a luminescent molecule, organic light emitting diode.



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Equipment

- DSC, SAXS
- Fluorescence, optical and infrared microscopy and spectroscopy
- Electro-optic characterization
- Fabrication and opto-electronic characterization of thin organic layers

Nanostructure Formation, Nano-Analytics and Photonic Materials
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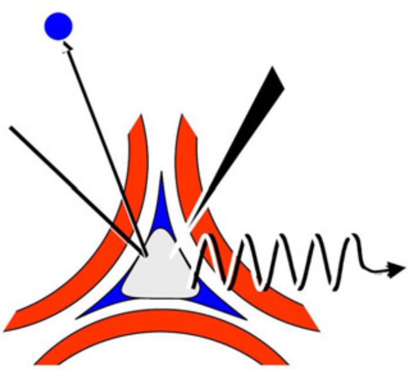
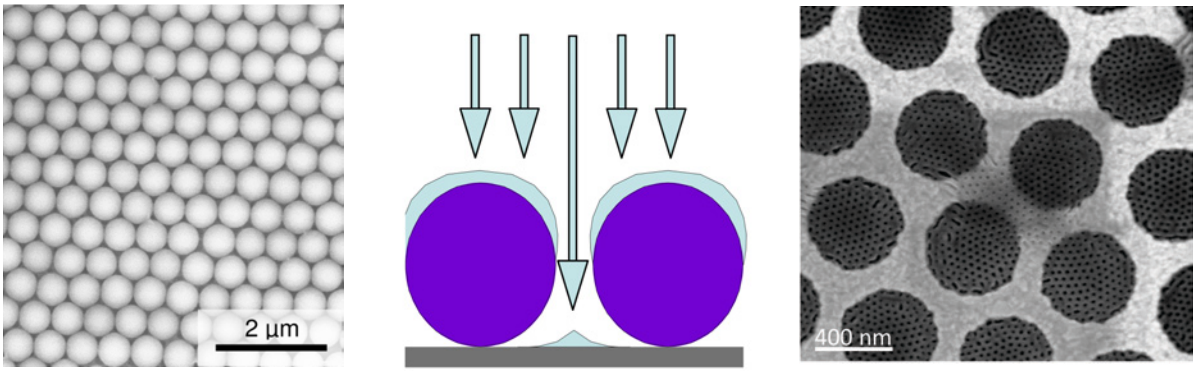
The ability to tailor the shape, the inner structure and chemical composition of solids at the nanoscale is the key to modern materials design and technology. Nanostructures are presently investigated for a wide range of applications in optics, electronics, energy harvesting, chemistry, biology and others. Accordingly, we use many different fabrication techniques to create nanomaterials. In order to fully exploit their technological potential, precise knowledge of the physical mechanisms influencing the interplay between materials fabrication conditions, resulting nanostructural properties and the macroscopic materials characteristics is required. To achieve this, state-of-the-art (analytical) electron microscopy is employed in our research group, allowing for materials characterization at the nanometer or even atomic level. Emphasis is placed on materials which are hot candidates for future optoelectronic and photonic devices, including 2D photonic crystals, plasmonic nanostructures and wide band-gap semiconductor systems. Different bottom-up patterning techniques are combined to obtain nanoscale structures with maximum control at minimum cost, which is beneficial for any applications.





SEM image of a monolayer of polystyrene spheres on a silicon substrate, schematics of a deposition process through such a monolayer, and hierarchically nanopatterned mask created using NSL, reactive ion etching, physical vapor deposition and BCP lithography.

Nanopatterning using self-organization

Nanostructured surfaces with minimum feature sizes in the range of few ten to few hundreds of nanometers are the basis of many applications in optoelectronics, photonics, sensors, catalysis, biomed and others. Frequently, either a periodic arrangement of small motives or at least a homogeneous surface coverage with nano-objects is required, preferably on a large-area surface.

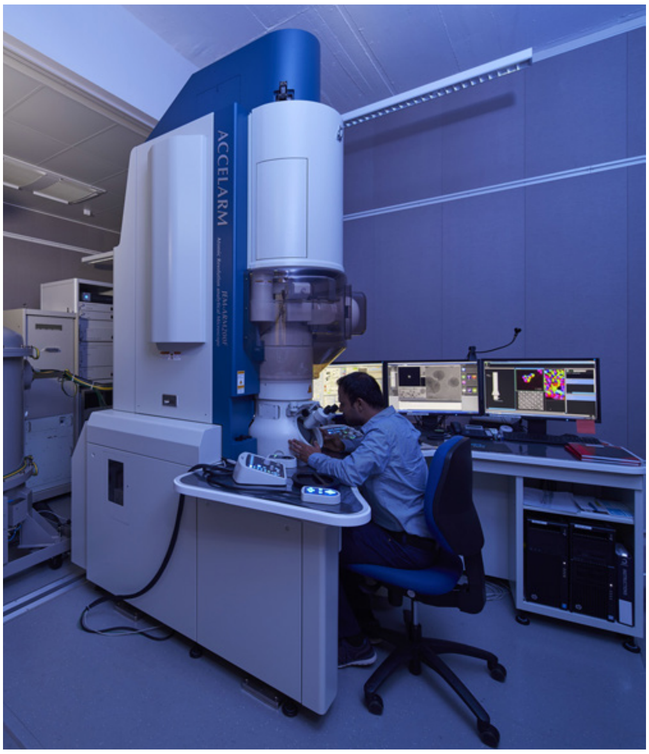
Self-organization based techniques provide cost-effective, fast and materials-general approaches to create periodic nanoscale surface patterns on large area substrates. A popular technique is nanosphere lithography (NSL), also called natural lithography. It is based on the self-organization of equally sized nanospheres from a colloidal suspension in a hexagonally close-packed mono- or double-layer, acting as a shadow mask on a substrate surface. At the free spaces in between each triple of neighbouring spheres in a colloidal monolayer small amounts of material can be either deposited onto or removed from the subjacent substrate. Our research team explores techniques to create NSL masks on large-area substrates and with good control of the mask position and perfection. Both, plain and prepatterned, flat and curved 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. Different materials deposition and modification processes (e.g. electron beam deposition, sputtering, plasma enhanced chemical vapour deposition, ion implantation) are combined with the NSL method in order to explore the potential of the NSL technique. Processes are explored which allow to manipulate the shape of mask openings and tailor complex surface nanopatterns. Optical and numerical tools are developed to control, predict and analyse the patterning process. Applications in different areas such as nano-optics, semiconductor heteroepitaxy and the precision placement of anorganic and organic (bio) nanoparticles are investigated. For self-organized patterns with feature sizes smaller than 20 nm one needs building-blocks smaller than the spheres used in NSL, i.e. units in the size range of macromolecules. We use the thermally induced self-organization of block-copolymers (BCP) in order to create surface patterns with sub-20 nm sizes. BCP-lithography is combined with NSL in order to create hierarchically patterned surfaces.

Nanoheteroepitaxy

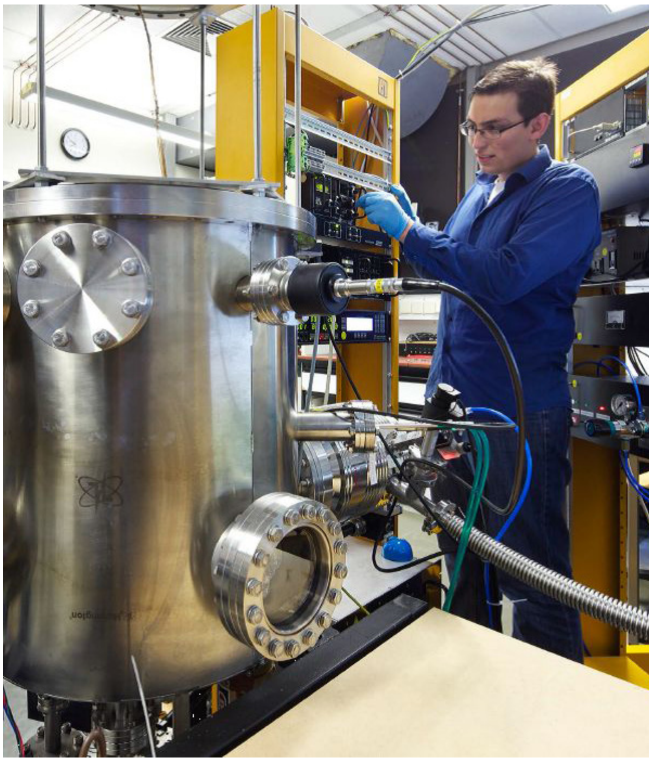
One of our main applications of self-organized nanopatterns is the improved heteroepitaxy of compound semiconductor layers on lattice mismatched substrates. Theories predict that below a certain threshold size the growth of semiconductor thin films on nanorods is possible without extended lattice defects even in the case of largely lattice mismatched substrates. This so called nanoheteroepitaxy is studied theoretically (continuum mechanics and molecular static simulations) and experimentally (surface patterning and microscopy) in cooperation with other CeOPP groups, which have the tools and experience in the molecular beam epitaxy (MBE) of compound semiconductor growth. Typical examples are GaN on patterned SiC substrates and InGaAs on pre-patterned GaAs, i.e. materials used for modern optoelectronic devices. The suppression of extended lattice defects in such materials is crucial for enhanced device performance.

Electron Microscopy

Nanostructured materials need to be inspected with respect to their morphology, internal structure, and overall as well as local chemical composition. For materials with small feature sizes this needs to be done at best possible spatial resolution, since macroscopic properties are frequently determined by the atomic structure at the surface or at internal interfaces. This is accomplished using atomic force microscopy (AFM), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM), complemented by analytical techniques such as energy dispersive X-ray spectroscopy (EDS) and electron energy loss spectroscopy (EELS). The group operates a state-of-the-art (scanning) transmission electron microscope, equipped with a cold field emission gun (for high energy resolution in the spectroscopy modes), Cs-corrector in the illumination system (for sub-Angstrom resolution in the STEM mode), EDS with a Si drift detector (for chemical element mapping), and a post-column energy filter for high-resolution (dual-) EELS. The latter technique allows for chemical element and bonding state determination with sub-nanometer resolution as well as mapping of optical and electronic properties such as the local band structure, plasmon excitations, and mapping of the dielectric function over a large energy range. In addition, the microscope is equipped with different STEM detectors allowing for direct imaging of individual atoms as well as internal electric and magnetic fields on a sub-nanometer scale. For the latter, a differential phase contrast (DPC-STEM) detector based on a 16-fold segmented photomultiplier system is available. Owing to the Cs-corrector, extreme spatial resolution is even achieved when decreasing the electron energy from the normal 200 keV to smaller values down to 30 keV, allowing to investigate even very beam sensitive materials with most of the techniques mentioned above. The combination of these techniques yields an atomic level understanding of macroscopic materials properties. As such knowledge is valuable also in many other areas of research and application, the group provides – together with colleagues in Bielefeld hosting a cryo-TEM for low-temperature investigations on soft matter – microscopy service for groups in and around OWL.



The new high-resolution (scanning) transmission electron microscope



Home-built electron beam evaporation system dedicated to the large-area fabrication of arrays of geometrically and chemically tailored plasmonic nanoparticles.

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- M. Sc. Syed Jahanzeb Azam
- M. Sc. Katharina Brassat
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- B. Sc. Dennis Drude
- B. Sc. Tim Eichelberger
- B. Sc. Michael Kismann
- B. Sc. Daniel Kool
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- Maren Kosanke
- Alexander Stratmann
- Mathias Strothmann
- Kevin Wielsch
- David Wolke
- Dipl.-Phys. Ing. Dipl. Math. Werner Sievers (technician)
- Jonas Hansmann (apprentice)
- Claudia Hagemeier (Team Assistent)
- Prof. Dr. Jörg K. N. Lindner

Equipment

- Jeol ARM 200F Cs cor. (S)TEM
- Jeol FX2000 TEM
- Jeol JSM 6300F SEM
- Jeol 6060 SEM with EDX
- Digital Instr. Dim. 3100 AFM
- Oxford Plasma Etcher RIE80+
- Oxford PECVD 80
- Oxford RIE 100
- ESR, PL, AFM, PVD

Nanophotonics and Nanomaterials
Prof. Dr. Cedrik Meier

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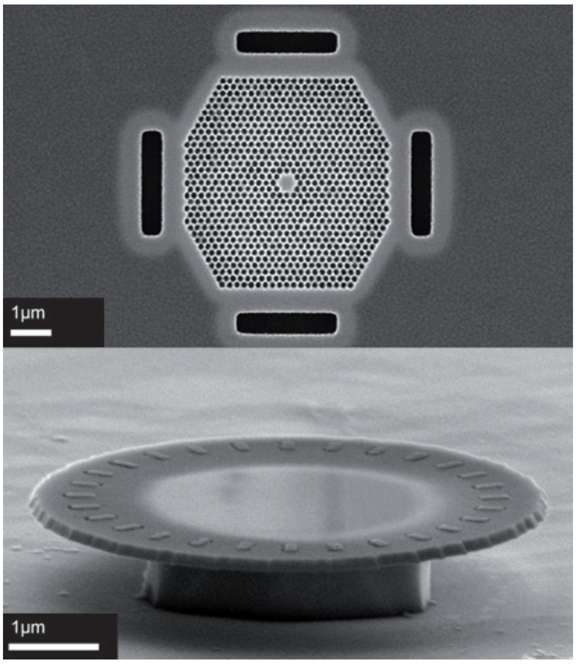
Photonic and plasmonic nanostructures made of ZnO-based materials are investigated in the Nanophotonics & Nanomaterials group.
By combination of high-quality fabrication techniques such as plasma-assisted molecular beam epitaxy with high-resolution patterning techniques such as electron beam lithography and plasma etching, sophisticated devices are formed enabling control of light-matter interaction.
Such devices are used for investigation of linear and nonlinear processes, such as higher-harmonic generation and multi-photon absorption.
Another important goal of the research activities in the group is to develop photonic devices with all-optical control, which could become key building blocks in photonic integrated circuits. Here, hybrid devices made from semiconductors and molecular materials are investigated.

Wide gap photonic devices

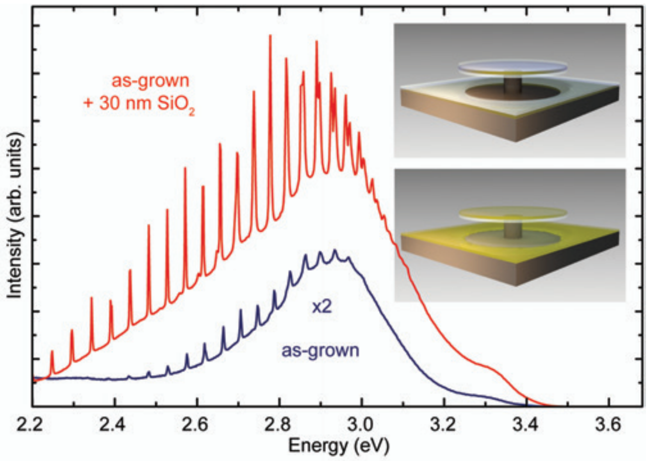
Zinc oxide (ZnO) is a very interesting material for photonic devices due to a number of unique features. Among those are the large band gap, covering the blue and UV spectral range, the large exciton binding energy (60 meV in bulk) and the lack of inversion symmetry, leading to strong and unusual nonlinear optical properties. A main focus of the research in the Nanophotonics & Nanomaterials group is to engineer low-dimensional systems and interfaces in order to obtain photonic devices with tailored linear or nonlinear optical properties. The combination of molecular beam epitaxy and electron beam lithography allows a high degree of freedom in the design and fabrication of novel devices. The goal is to develop highly nonlinear devices with controlled and predictable properties.

Novel optical material concepts and design methods

In order to obtain tailored photonic devices, it is often necessary to engineer the electronic properties of the materials as well as the photonic properties of the fabricated devices. The electronic properties, e.g., the band gap or the excitonic resonances of a material can within certain limits be engineered using molecular beam epitaxy. Using this technology, thin films can be grown in which quantum confinement leads to a tailored electronic structure. Molecular beam epitaxy can also be employed on patterned substrates, which allows to apply quantum confinement to more than one dimension, creating a new level of flexibility in structure design.
The strong excitonic properties of zinc oxide are closely linked to the dielectric properties of the material. In fact, the refractive index of ZnO is – in comparison with other semiconductors – comparably low, so that photonic devices made from monolithic structures are difficult to obtain. Here, it is desirable to employ membrane structures, so that the refractive index contrast to the surrounding air supports photonic confinement.



Top: ZnO-based photonic crystal membrane. Bottom: SiO_2-based nanoplasmonic ring resonator with Ag dipole antennas.

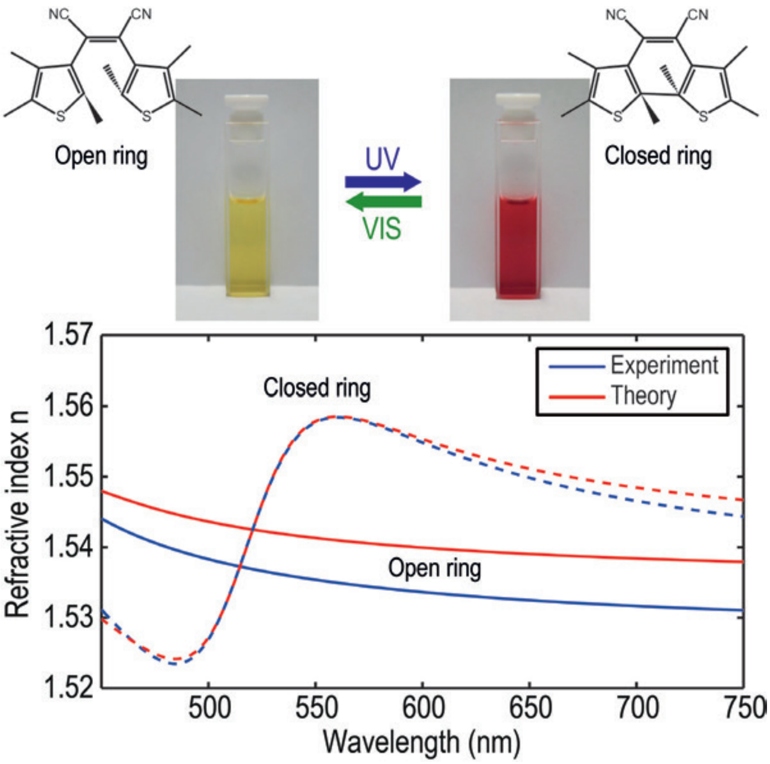


Broadband emitting photonic ring resonator made from low-temperature ZnO.

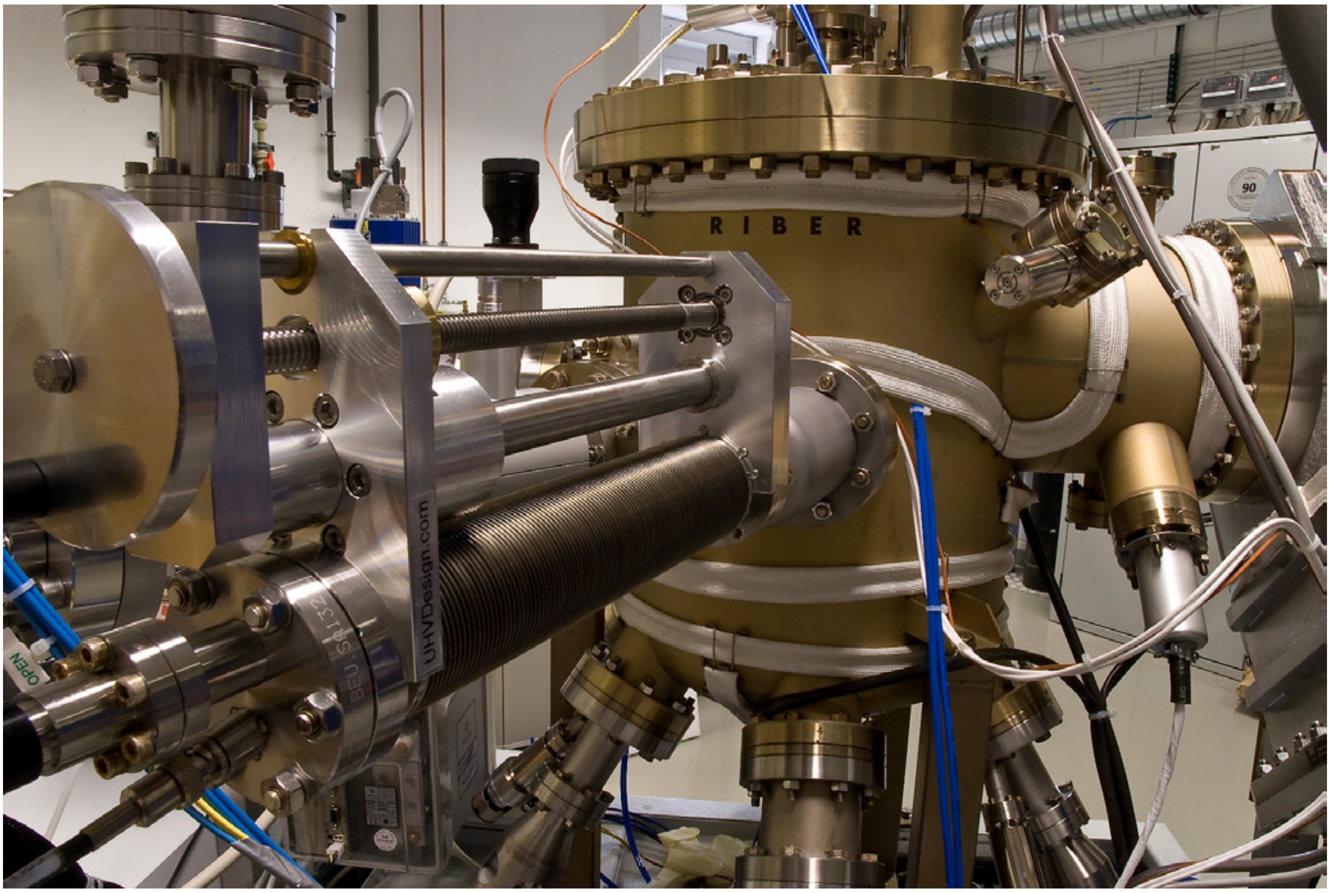
The strong polarity of ZnO, however, makes conventional wet etching techniques in this material system difficult. Therefore, the group has developed a number of different patterning techniques to tackle this problem and to achieve ZnO-based resonators with full photonic confinement in all three dimensions. To achieve even more control over the light field, we have also recently started to develop photonic/plasmonic hybrid devices in order to obtain strong light field localization which enables nonlinear processes in these devices.

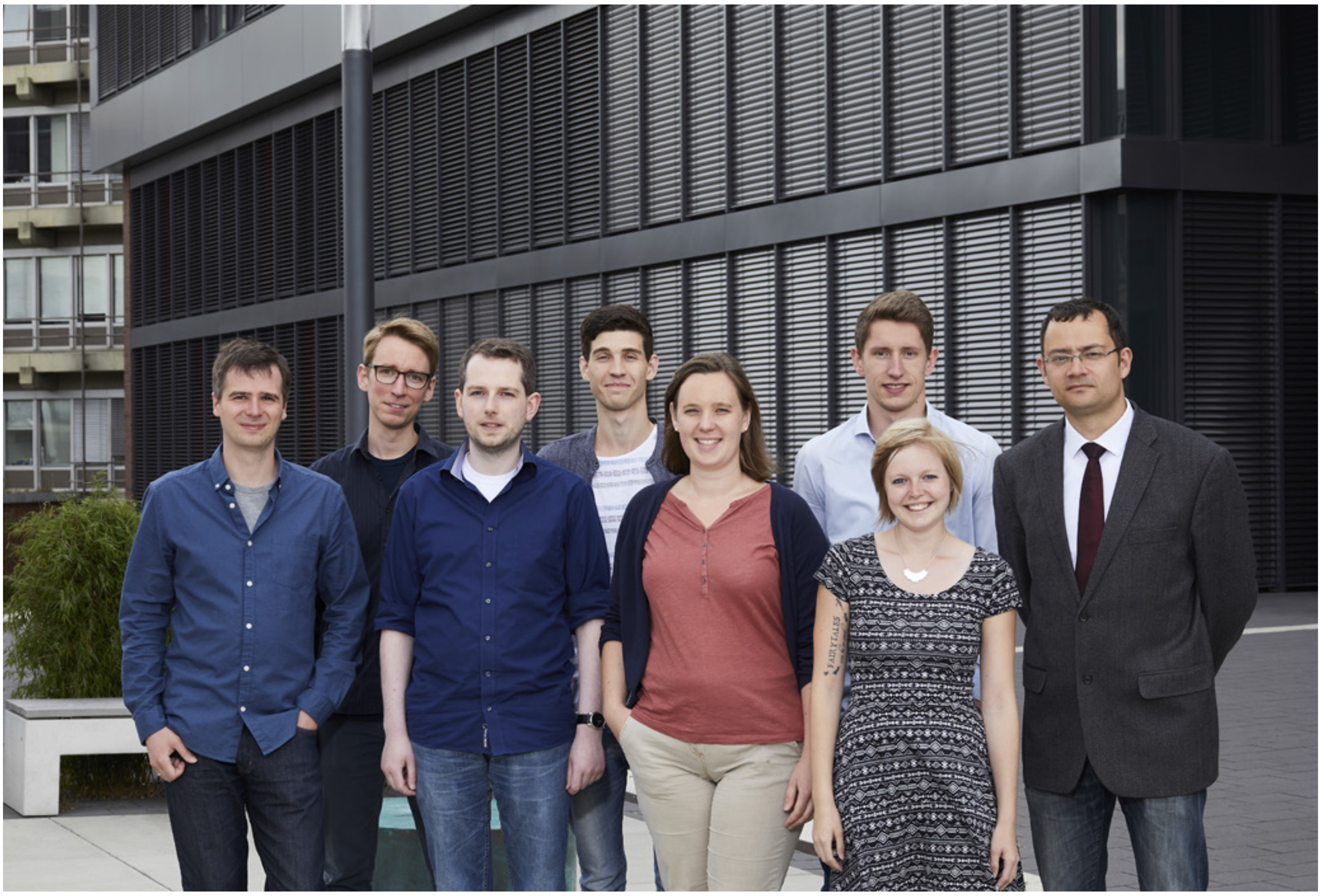
Molecular driven photonic switches

Another important focus of the research activities in the group is the development of hybrid devices made of semiconductors and molecular materials. For applications in photonics or plasmonics, photochromic molecules and liquid crystals are of special interest. In these systems it is often possible to control the dielectric function of the material by external parameters, such as temperature, electric fields or irradiation. An example is shown on the right, where the optical properties of the diarylethene molecule CMTE are shown. Upon irradiation with UV or VIS light, this molecule can be switched from an open ring to a closed ring configuration, which leads to a significant change in the refractive index. In combination with semiconductors, hybrid devices can be fabricated which are promising for novel application such as all-optical switching.



Optical properties of the photochromic diarylethene CMTE.





Group Members

- Dr. Christina Bader
- M. Sc. Sandro Hoffmann
- M. Sc. Nils Weber
- Prof. Dr. Cedrik Meier

Equipment

- Plasma-assisted molecular beam epitaxy for ZnO-based materials
- Electron beam microscopy
- Electron beam lithography
- Plasma etching
- Thin film processing
- Spectroscopic ellipsometry
- UV/NIR micro photoluminescence
- UV/VIS transmission spectroscopy

Computational Optoelectronics and Photonics

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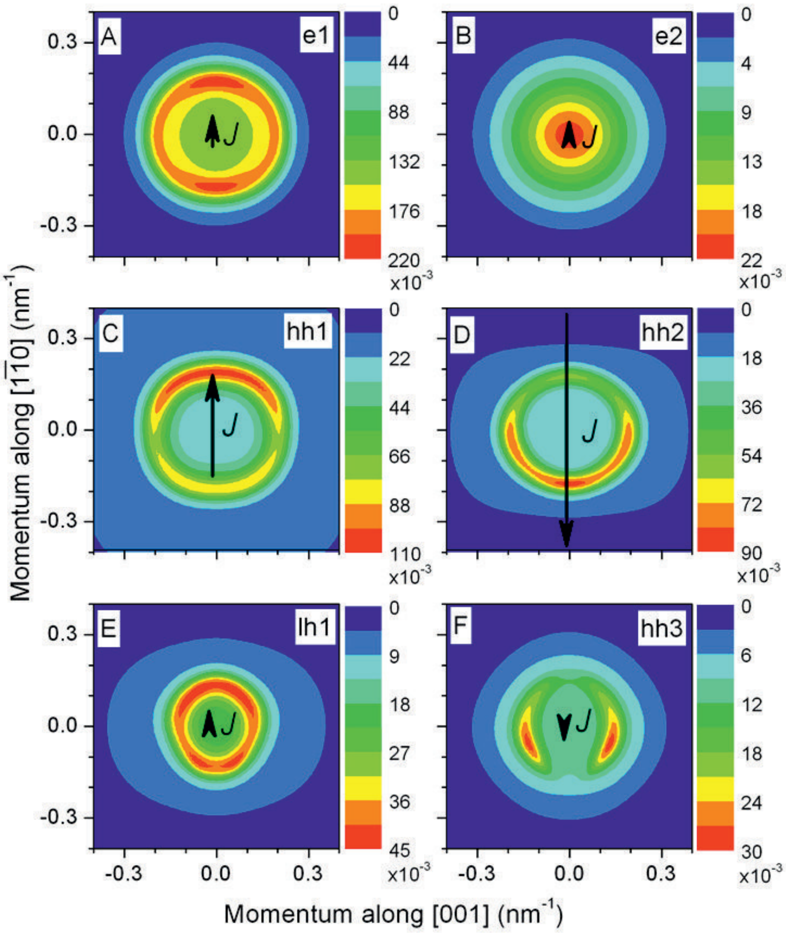
Nanostructures offer fascinating possibilities to modify both the electronic states and the light field. Suitably designed systems allow one to control the light matter interaction and thus to achieve and utilize desired linear and nonlinear optical and electronic properties.
The main goal of our research is the development of microscopic theoretical approaches that are able to accurately describe optoelectronic and photonic nanostructures. In our computations many-body effects and the self-consistent evaluation of the coupled propagation of the light field and of the material excitations is often of great importance. The required computer programs are developed and solved numerically by our group.
Topics of particular relevance are nonlinear optical effects and the ultrafast coherent quantum dynamics. Often the obtained results are used to analyze specific measurements or for the prediction of interesting novel experimental configurations.

Ultrafast Photocurrents

In certain low-symmetry nanostructures or by using specially designed laser pulses it is possible to optically generate electronic currents on ultrafast femtosecond (10^{-15} s) time scales. Such photo-currents can also be spin-polarized and even a pure spin current, i.e., a spin transport that is not accompanied by a charge transport can be realized. Such optoelectronic effects allow one to monitor transport on ultrafast time scales.

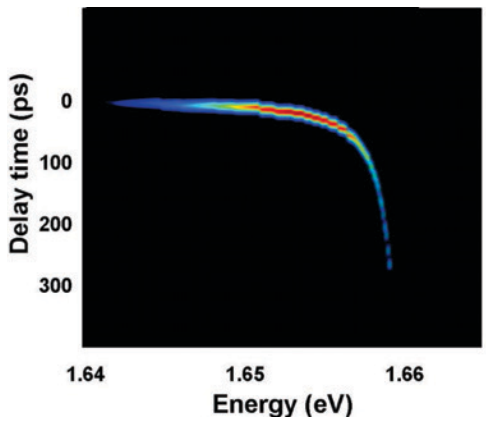
We analyze the generation and the coherent ultrafast dynamics of charge- and spin-photocurrents in semiconductors and semiconductor nanostructures by numerical simulations that are based on a microscopic theory in collaboration with experimental partners.



Electron distributions in momentum space in different bands of a quantum well. The arrows indicate the direction and strength of the photocurrents J.

Nonlinear Light Propagation in Semiconductors

Together with experimental groups we study the propagation of light pulses through wide-gap semiconductors in waveguide structures. Near an optical, e.g., excitonic, resonance spectral components of a light pulse are significantly slowed down when moving through the sample. This effect of the light-matter interaction is present already in the linear optical regime. We aim at describing the light propagation in the nonlinear regime and for more complex scenarios where, e.g., several pulses interact, and the time delay can be controlled by the pulse intensity and/or by additional control pulses.

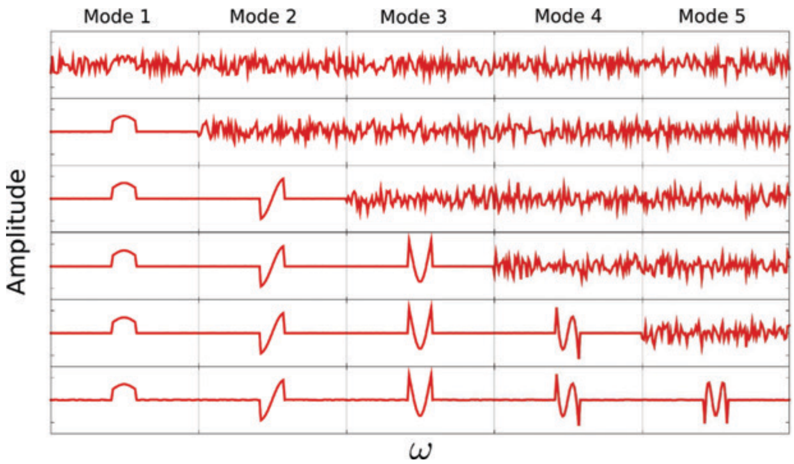


Slow down of the light propagation near an excitonic resonance.

Nonlinear pulse propagation can be a key feature for light management in novel nanophotonic circuits by, e.g., providing delay lines by which the arrival time of light pulses at certain components can be controlled accurately.

On-Chip Quantum Optics

Together with experimental colleagues we aim at developing an on-chip quantum device in order to demonstrate the peculiarities of quantum mechanics. The so-called Hong–Ou–Mandel effect will be realized by using photons that are generated on-chip by a tailored parametric down-conversion process. In the envisioned layout it is planned to achieve the non-classical Hong-Ou-Mandel interference and a complex mix of polarization and time-delay properties will be important.

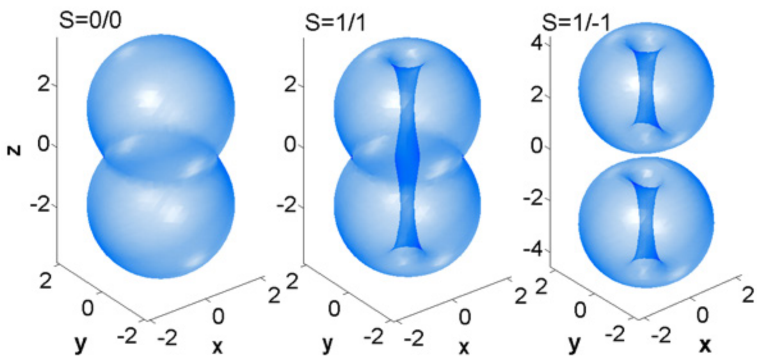


Finding broadband modes by an evolutionary optimization process.

We have already analyzed broadband modes that were generated in a related down-conversion scenario. By applying an evolutionary algorithm we computed accurately modes which can be used for measurements after they passed through a frequency filter.

Nonlinear Dynamics of Multi-Dimensional Light and Matter Waves

The motivation of this research is to discover novel types of nonlinear modes in three-dimensional media as well as novel persistent dynamical regimes. These modes can describe a multidimension-al Bose-Einstein condensate as well as multidimensional lights bullets.



Three-dimensional dipole modes consisting of solitons, co-rotating vortices, and counter-rotating vortices.

For example, we study the dynamical behavior of stable structures consisting of vortex tori as soliton gyroscopes. Indeed, these objects seem qualitatively similar to mechanical gyroscopes, whose most remarkable dynamical property is that the application of a torque perpendicular to the original angular momentum gives rise to a precession. We already demonstrated three dimensional bound states consisting of multiple toroidal vortices sharing the same vertical axis having identical or different values of the topological charge („hybrids“). Furthermore, the nonlinear dynamics of complex three-dimensional self-accelerating Airy light bullets, including those carrying angular momentum is investigated.

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- Dr. Wolf-Rüdiger Hannes
- B. Sc. Andreas Nikitin
- Dr. Reinold Podzimski
- Dr. Matthias Reichelt
- B. Sc. Alexander Trautmann
- B. Sc. Elisabeth Wagner
- Simone Lange (team assistant)
- Prof. Dr. Torsten Meier

Methods

- Microscopic quantum theory for the optical and electronic properties of nanostructures including nonlinearities and ultrafast coherent effects
- Electromagnetic field simulations in photonic nanostructures

Optical Communication and High-Frequency Engineering

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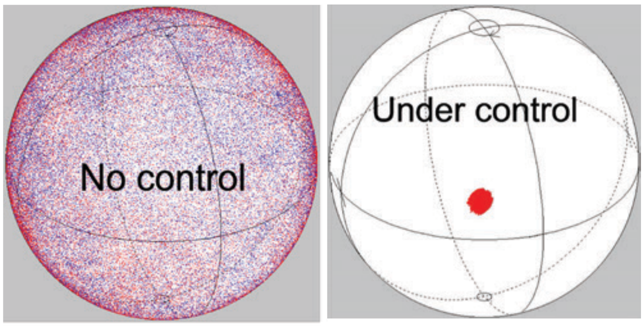
Optical communication transmits information for internet and telephone. At 1.55 µm wavelength the attenuation of the glass fibers is so small that after 100 km there is still 1/100 of the transmitted optical power available. The bandwidth is about 1/5 of the light frequency, roughly 40 THz. This is ~1000 times as much as in the whole radio frequency spectrum currently in use. About 10 THz can be utilized very cost-efficiently, by means of optical amplifiers. The superb fiber properties have made internet and low-cost telephony possible. Growth of data communication is enormous, in the order of 40% 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 multiplying optical information density. Phase-noise tolerant coherent receivers provide best performance and permit equalization of fiber distortions in the electronic domain.

About Attoseconds, Kiloradians/s, Terabit/s, Lithium Niobate and Microelectronics: Modulation and Equalization of Optical Data Signals

Optical communication utilizes lightwave guides made from silica glass for information transmission in the worldwide data and telephone net. The available bandwidth of the glass fiber is huge and its attenuation is extremely small.

Compensation of Linear Optical Distortion

Just as a short earth quake agitates a distant seismometer for a longer time short data pulses are temporally dispersed in glass fibers by chromatic dispersion. Neighbor pulses overlap and become undetectable. For equalization (compensation) we measure the dispersion with an extremely cost-effective method which detects repeated, regular light pulse propagation delay changes with an accuracy of **100 attoseconds** (0.000,000,000,000,000.1 seconds). Due to unwanted elliptical rather than circular fibercore cross-sections the light pulses are subject to another dispersion that depends on the polarization direction. We have compensated this **polarization mode dispersion** at the receive end using an integrated optical **Lithium Niobate** component which we have proposed. We have implemented **optical polarization controllers** with an unrivaled tracking speed of up to **140 kiloradians/s**, corresponding to more than 10000 full polarization rotations per second (spin-off Novoptel GmbH, 2010).



Polarization states on Poincaré sphere without/ with endless polarization control

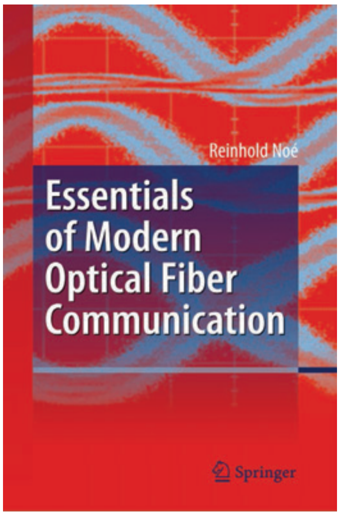
Awards received for ultrafast optical polarization control

Advanced Optical Modulation Formats

With **2 polarization directions and ≥4 phases and amplitudes** of the light we transmit in each data symbol ≥16 different states rather than the traditional 2 (light on/off). This way we have set up a capacity world record of **5,94 Terabit/s** (5,940,000,000,000 bit per second) over a 324 km distance (2005). The setup is seen on the picture at the right.

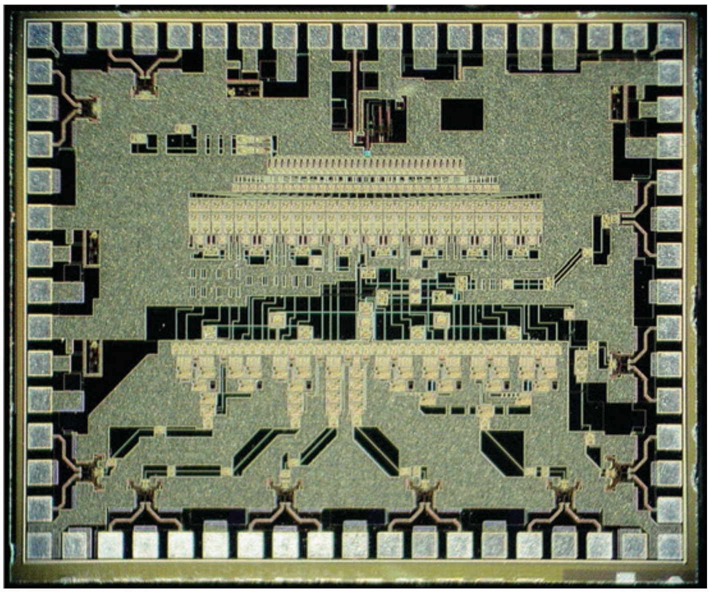
Furthermore, with fast polarization control, we have achieved a bitrate world record of 200 Gigabit/s over a 430 km distance for a single channel (2010). As of 2014, the used symbol rate 50 Gbaud is still a world record for realtime transmission with ≥4 bit/symbol.

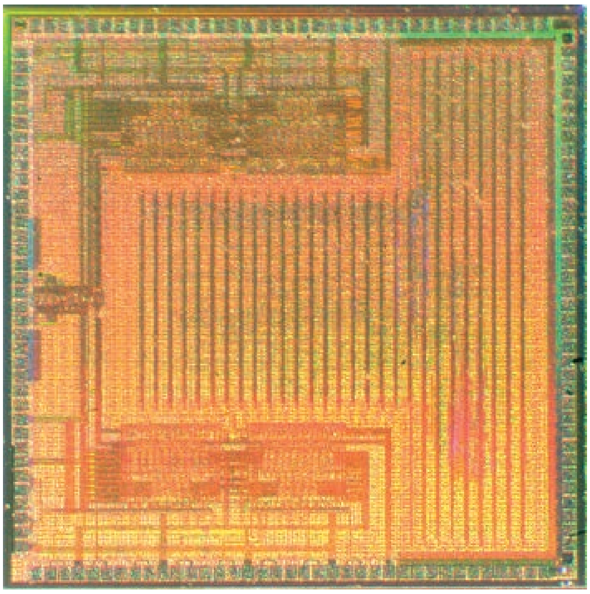
The innovation prize 2008 of the Land Nordrhein-Westfalen in the category innovation was awarded to Reinhold Noé and Ulrich Rückert.



Textbook, contains also our research results (2010).

Rather than – as before – in interferometers the 4 phase states can also be demodulated synchronously in coherent optical superheterodyne receivers, which increases sensitivity and makes it possible to compensate signals distortions very cost-effectively. We have demonstrated such a system for the first time worldwide with standard lasers (2006), have equipped it with an electronic polarization control and enhanced it for 2 polarizations (2007), with a tracking speed of 40 kiloradians/s. For electronic signal processing we have implemented a microelectronic 5-Bit analog-to-digital converter with 12,5 GHz sampling frequency (picture bottom left) and a digital signal processor (picture bottom right). This coherent optical transmission technique has revolutionized long-distance optical data transmission.





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- Dr.-Ing. Benjamin Koch
- Dr.-Ing. Vitali Mirvoda
- M. Sc. Muhammad F. Panhwar
- Dr.-Ing. David Sandel
- Dr. Guangjun Shan
- Gerhard Wieseler
- Prof. Dr.-Ing. Reinhold Noé

Equipment

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

Optoelectronic Materials and Devices

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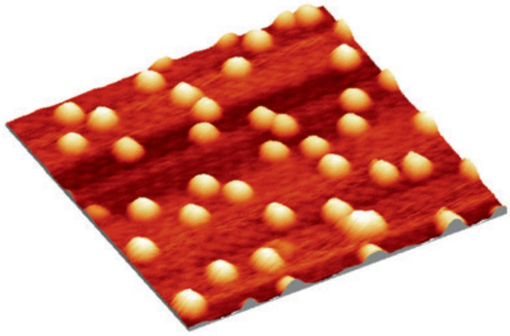
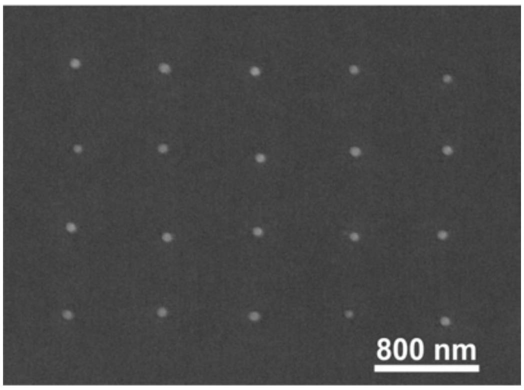
The group for Optoelectronic Materials and Devices at the University of Paderborn was established in 2012 and focuses its research on the fabrication and characterization of semiconductor heterostructures and heterostructure based devices. We employ molecular beam epitaxy, which allows the fabrication of heterostructures with monolayer precision opening the possibility to engineer the band structure in one to three dimensions. These artificial potential landscapes show a wealth of new interesting physical phenomena and allow for novel or improved optoelectronic devices.
To realize the full potential of the heterostructures, the material has to be of highest quality with respect to crystal defects and impurity atoms. To optimize the growth process, the structural, optical and electrical properties of the heterostructures are investigated by numerous methods.
Out of the optimized heterostructues, functional structures as micro-resonators or devices as diodes are fabricated and characterized.

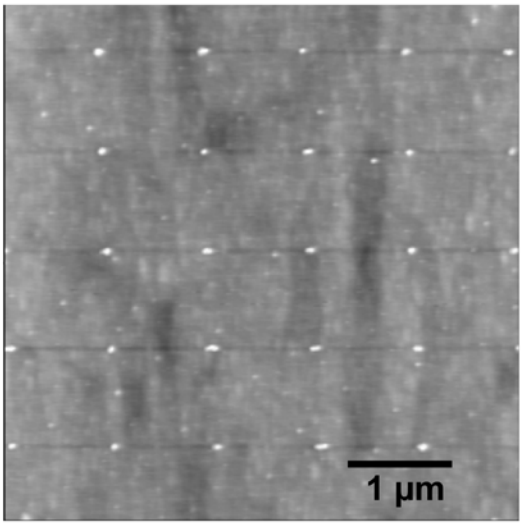
Nanostructures based on group-III arsenides and antimonides

Group-III arsenides and antimonides cover with their bandgap the near-infrared spectral range including the important optical C-band (1.55 µm) for fibre based communication. Based on these materials, we fabricate heterostructures with novel physical properties, especially carrier confinement in one or more dimensions, by molecular beam epitaxy (MBE). One research focus is on the fabrication of semiconductor quantum dots by self-assembled growth, especially in the (In,Ga)As-system. In this mode islands are formed due to a lattice mismatch between the substrate and the film (strain-driven island formation). The islands are then overgrown by the substrate material again. If the island material has a smaller bandgap, the carriers are confined to the island region. This confinement on the nanometre scale results in atomically sharp energy levels for the carriers. This means, quantum dots can be considered as artificial atoms within a semiconductor matrix, which results in many interesting electrical and optical properties. For example, semiconductor quantum dots are envisioned as essential building blocks in solid state realizations of devices for quantum communication, e. g., solid state based single photon emitters.



Atomic Force Microscopy image (0.5×0.5 µm2) of InAs quantum dots on a GaAs(100) surface





Site-controlled quantum dots:
InAs quantum dots by growth on pre-patterned substrates (top) ; by Ga droplet epitaxy through a mask (bottom)

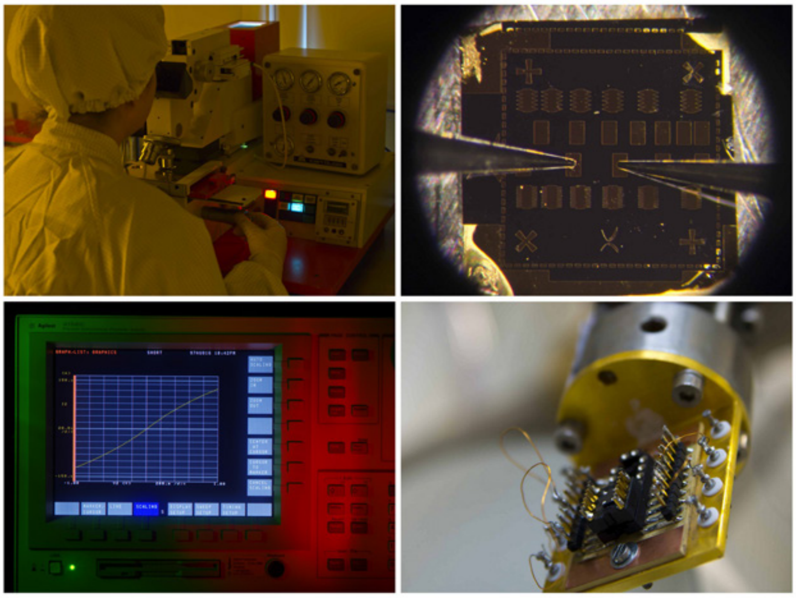
In addition to quantum dot formation via strain driven self-assembly, we fabricate quantum dots by droplet epitaxy. Here the group-III element, e. g., Ga or In, is deposited in a separate step and nanoscale droplets are formed on the surface. In a second step, these droplets are crystalized by supplying Arsenic as group-V element. This method allows forming quantum dots in material systems where the strain-driven approach fails.

In general, the islands as well as the droplets nucleate randomly on the surface, which is a drawback when it comes to device integration of a single quantum dot. But by ether growing on pre-patterned substrates or by local material deposition employing a mask, we are able to fabricate the quantum dots at predefined positions.

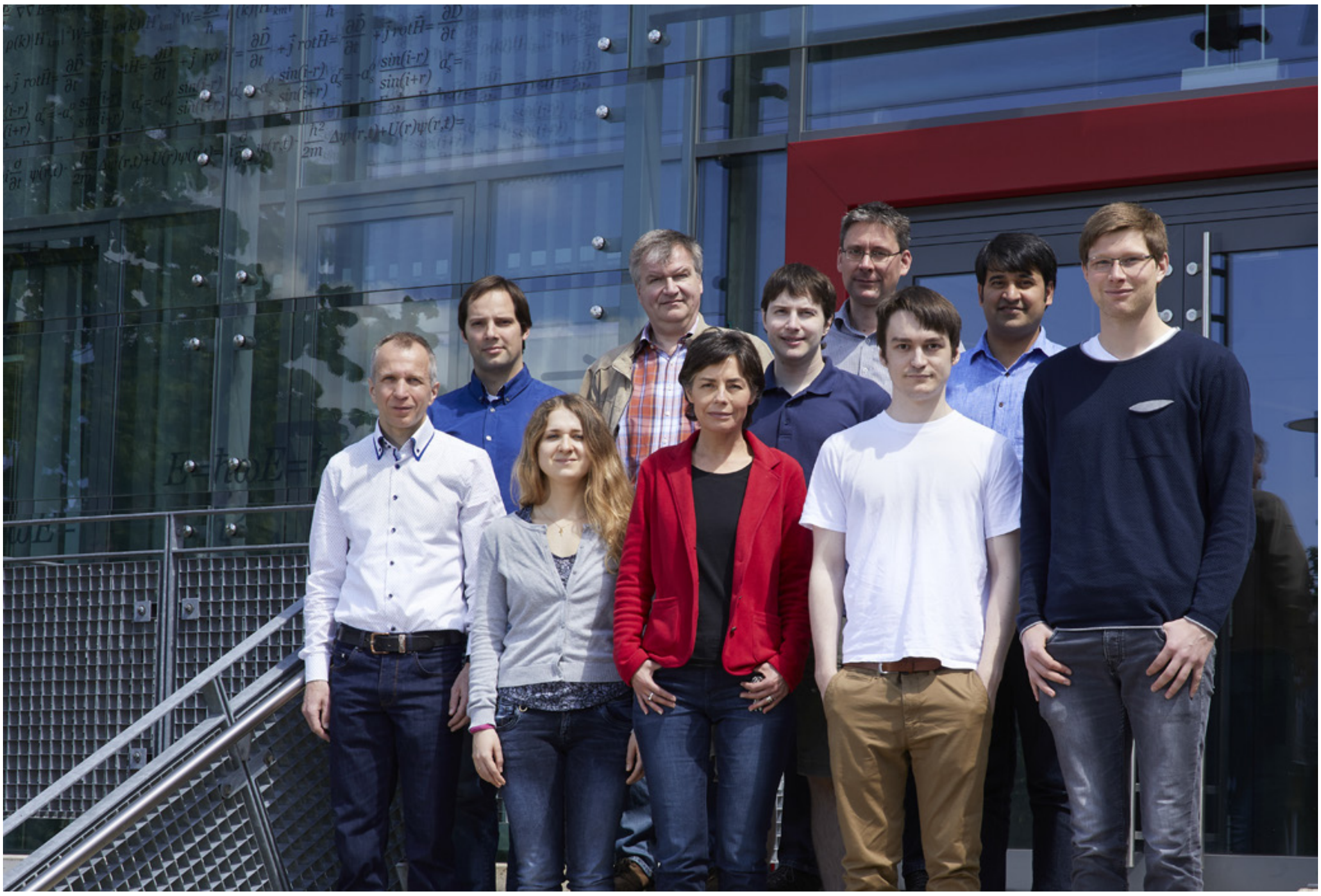
Another research focus is the fabrication of photonic structures to enhance the light-matter interaction. In particular, we grow AlAs/GaAs-based microcavities with embedded quantum dots. These structures allow for enhanced light out-coupling efficiency and are interesting for quantum optical experiments with single quantum dots.

Electrical and optical characterization

We characterize the structural, electrical and optical properties of the semiconductor heterostructures and feedback the results to optimize the growth process. We employ for example high-resolution X-ray diffraction, capacitance-voltage- and current-voltage spectroscopy, Hall measurements and photoluminescence (PL) spectroscopy. All measurements can be performed at low temperatures to make quantum effects detectable. We also fabricate functional structures or devices from the in-house grown heterostructures and characterize them electrically and optically. In our group, also a set-up for low-temperature electroluminescence measurements exists.



Photolithography, Tip measurement setup with sample, cold finger for measurements at low temperatures, parameter analyzer (clockwise from top left)



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Equipment

- Molecular beam epitaxy systems for III-V compound semiconductors
- High resolution X-ray diffraction
- Electrical characterization at low temperatures (e. g. Hall measurements)
- Photoluminescence spectroscopy
- Optical lithography and wet chemical etching

System and Circuit Design

Prof. Dr. Christoph Scheytt

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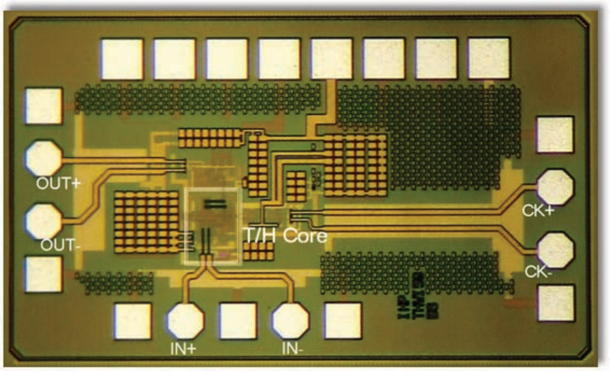
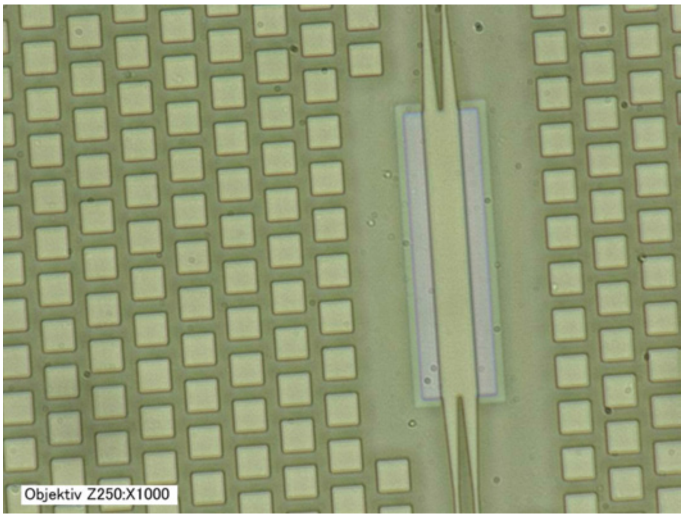
The evolution of silicon semiconductor technology moves basically into two directions. On one side scaling of transistors down to ever smaller geometry is continuing. This is often referred to as the "More Moore" direction according to Gordon Moore, the former president of Intel. On the other hand a diversification of silicon-based technologies ("More than Moore") is taking place in both academia and industry. This has led to exciting new devices such as MEMS, SiGe heterobipolar transistors, silicon photonics, or hetero-integration of III-V semiconductors on silicon.
Future optical communications and sensing applications will benefit from the diverse functionality of silicon technology, its capability to integrate and miniaturize. This will allow to realize complex optics, opto-electronics, analog electronics together with complex digital logic on a single chip. Our research focuses on the design of integrated circuits and systems for optical communication and sensing applications making use of "More than Moore" technologies.

High-Frequency Broadband IC Design for Optical Communications



Transimpedance amplifier with 40 Gbps data rate

Optical fibers offer THz of signal bandwidth, which is much more than current lasers, modulators, photo detectors or broadband electronic ICs can achieve. Hence the opto-electronic and electronic circuits usually come as the major bottleneck in optical communication systems. The design of extreme broadband electro-optical transmitters and receivers is challenging in terms of precise modelling of high-frequency passive and active devices, circuit topologies, high-frequency assembly, and packaging. Usually a co-design approach comprising electronic circuit design and simulation, optical device modeling, and high-frequency and passives simulation is required to achieve the desired results and mitigate unwanted parasitic effects. We have investigated and realized a broad range of laser and Mach-Zehnder-Modulator driver ICs, transimpedance amplifiers, as well as fast data converters and clock and data recovery ICs for optical communication links from 10 to over 100 Gbit/s.



90 degree hybrid in silicon photonics technology

Silicon Photonics System-on-Chip Design

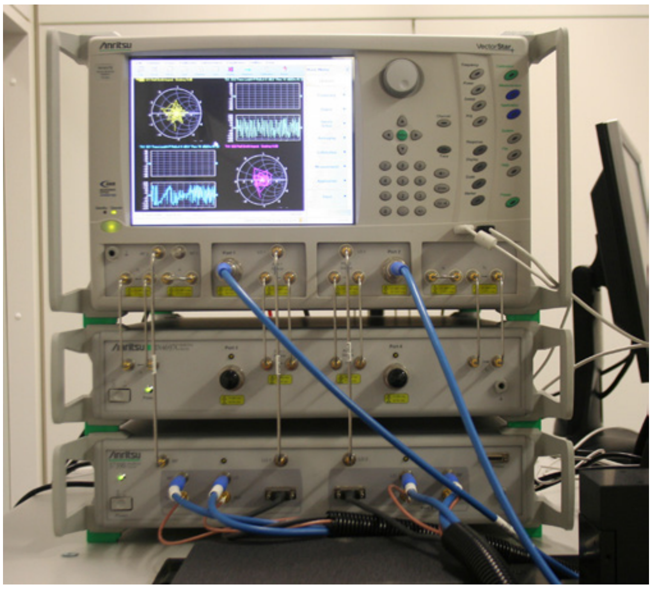
In Silicon photonics technology the integration of silicon waveguides, Germanium photo detectors and optical modulators together with electronic circuitry allows for realization of the “Silicon-Photonics System-on-Chip”. We model and design optical and opto-electronic on-chip devices and integrate them with electronic circuitry. We have access to a foundry partner which offers a silicon photonics BiCMOS technology with fast heterobipolar SiGe transistors which are especially suitable for very high frequency applications. Our research in silicon photonics targets high-speed integrate electronic photonics ICs (EPICs) transmitters and receivers for optical communications applications.

Opto-Electronic Sensor Design

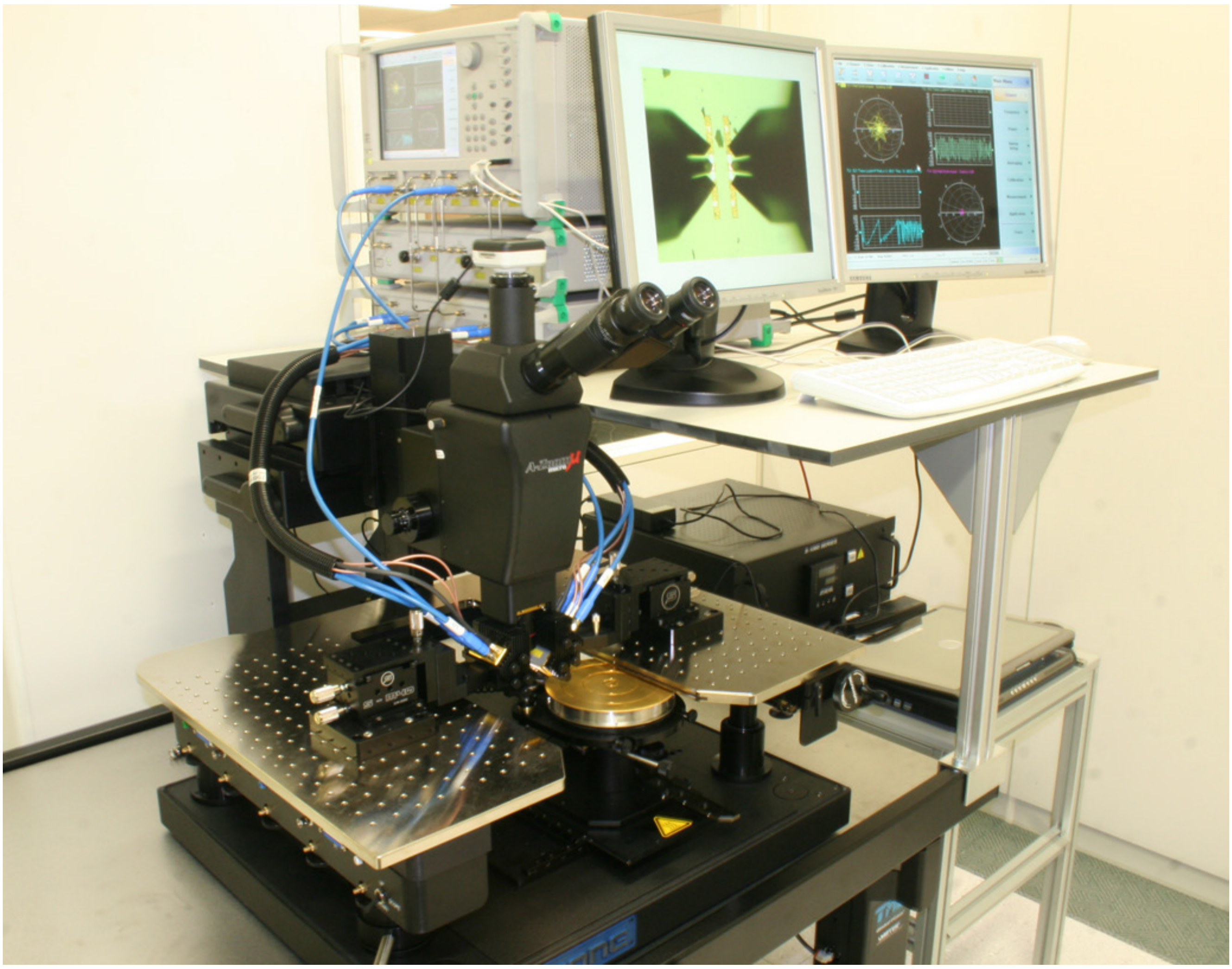
Besides optical communications the major other application area of opto-electronic devices is sensing. An optical sensor together with its electronic readout and signal conditioning circuitry represents a mixed-signal system where each component has to be tailored appropriately to achieve a desirable combination of different sensor properties such as specificity, sensitivity, precision, signal bandwidth, power dissipation etc. Furthermore integration of sensing principles on an IC is often desired. The design of opto-electronic sensor circuits requires a thorough understanding of both the optical and electronic domain, optical and electrical device modelling, co-simulation and co-design.

The HF / Broadband Lab

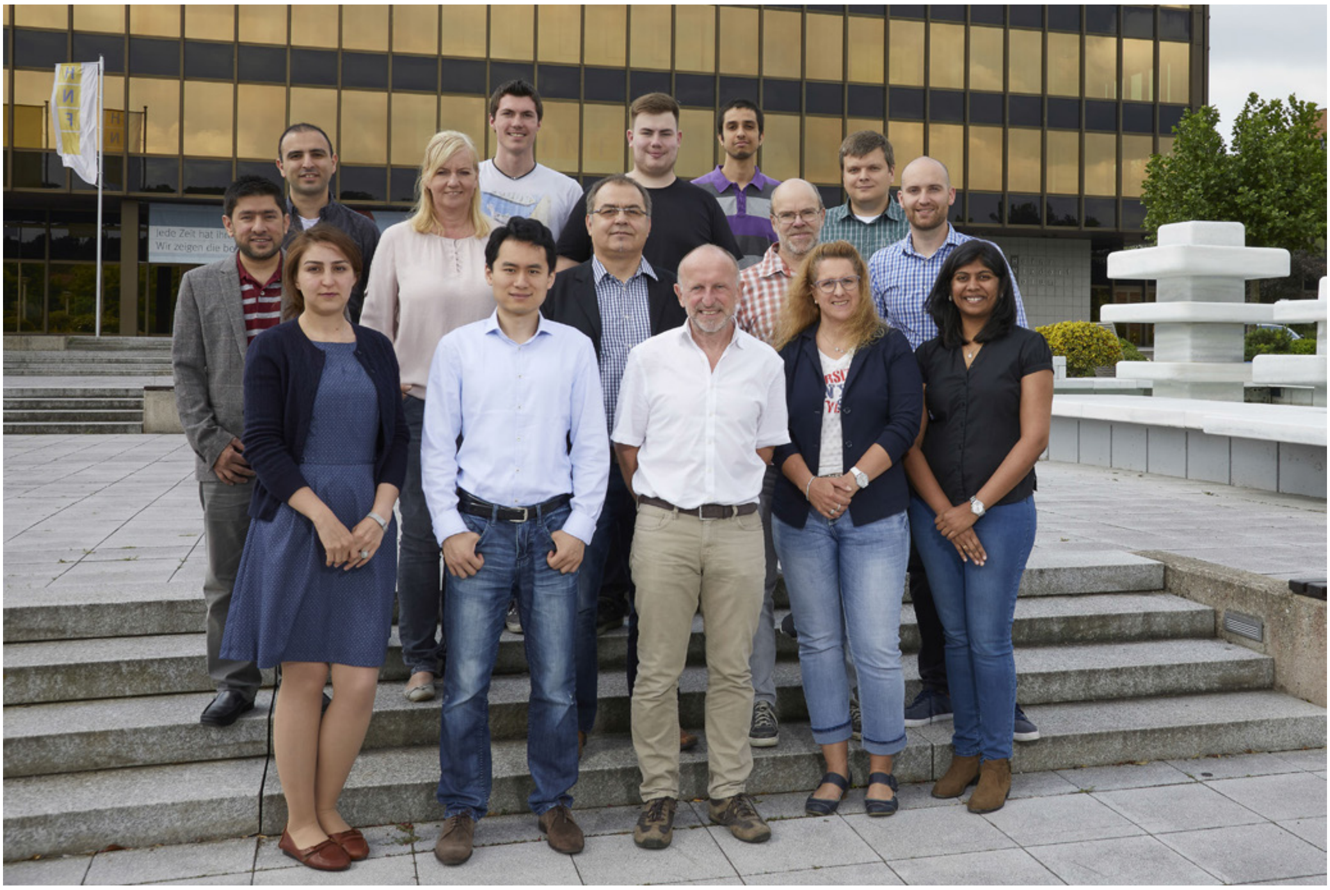
In our HF / Broadband Lab we can measure electronic and opto-electronic circuits on-wafer with a manual wafer-probe station. S-parameters can be measured from below 100 kHz up to 70 GHz (4-port) and up to 110 GHz (2-port). This includes also the possibility to measure spectra in this frequency range. Furthermore we have an ultra-fast bit pattern generator (4x32 Gigabit per second) and a broadband sampling oscilloscope capable to measure digital signals up to 100 Gigabit per second.



Vector Network Analyzer for S-parameter measurements up to 110 GHz



Wafer Probe Station



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Equipment

- Wafer Probe Station
- Vector Network Analyzer 110 GHz
- Bit pattern generator 128 Gigabit per second
- Sampling Oscilloscope >70 GHz Bandwidth
- Logic Analyzer with 6000 channels
- Optical Sources and Detector

Many-Body Theory of Solids
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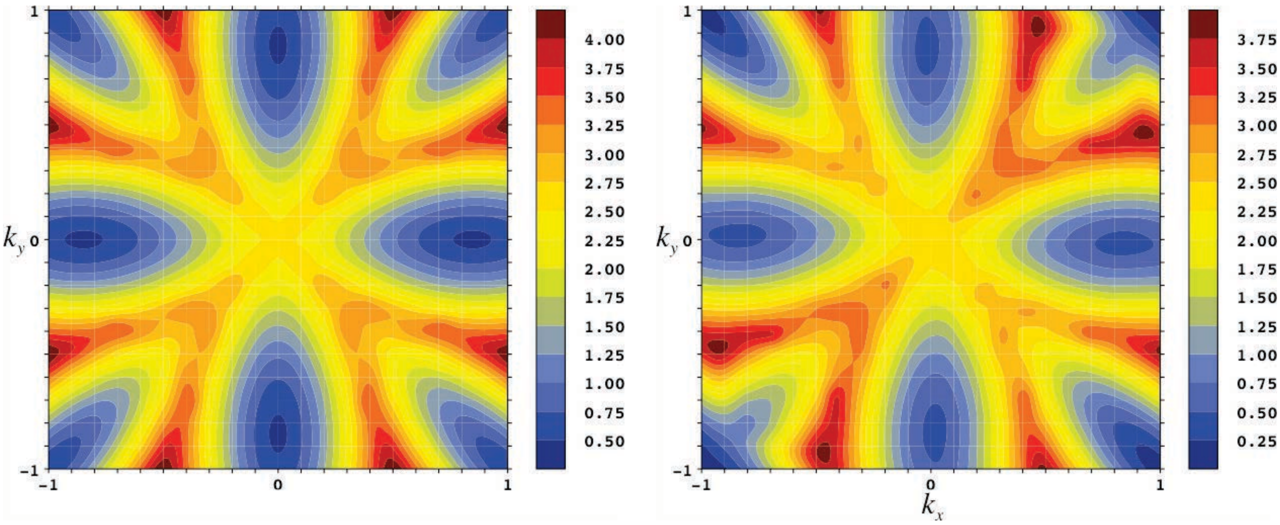
Accurate quantitative predictions of the optical, electronic and magnetic properties of materials are possible with a combination of modern ab initio quantum-mechanical methods and large-scale numerical calculations. From microscopic simulations of the dynamics of electrons and atomic nuclei in the presence of external fields, spectral functions as well as other observable material properties can thus be derived without relying on empirical parameters or models. The results complement experimental investigations by providing additional physical insight.

The Many-Body Theory of Solids group focuses on the development and application of efficient quantum-mechanical techniques that treat the electronic correlation as well as the light-matter interaction at a level appropriate for quantitative investigations in materials science. Of particular interest are the electronic band structures and photoemission spectra of crystalline solids and their linear and nonlinear optical properties. In addition, the characteristic spin excitations and the magnetic properties of materials are studied with a view to future spintronics applications.

Electronic band structures

Key material characteristics like the fundamental energy gaps of semiconductors or the effective masses of charge carriers in metals, which determine the performance in technological devices, are implied in the electronic band structure. While this can be readily interpreted in a single-particle framework, correlation effects stemming from the fermionic nature of the electrons and their mutual Coulomb interaction strongly influence the dispersion of the energy bands and must be included to achieve quantitative agreement with experimental photoemission spectroscopy. For this reason we employ modern quantum-mechanical many-body techniques like the GW approximation for the dynamic self-energy, to analyze the electronic structure of technologically interesting inorganic and organic materials. Our ab initio approach enables reliable predictions in cases where experimental data is absent or ambiguous, including the role of surfaces, interfaces, defects and strain.



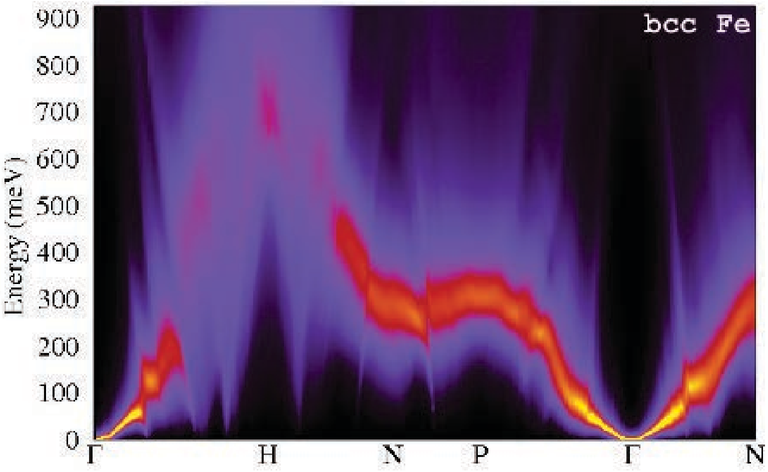
Energy dispersion of the lowest conduction band of silicon without strain (left) and with 3% uniaxial strain along the [110] direction (right).

Linear and nonlinear optical spectra

Optical excitations in solids are characterized by the creation of electron-hole pairs (excitons) and other collective modes, such as plasmons, which appear as prominent and often dominant features in absorption spectra. As these cannot be interpreted within a simple single-particle picture, their theoretical description poses a major challenge, but state-of-the-art methods like time-dependent density-functional theory or many-body perturbation theory in combination with the Bethe-Salpeter equation allow accurate ab initio calculations of optical spectra. We use these methods to study the linear and nonlinear optical properties of technologically relevant materials, such as lithium niobate. In particular, we investigate how the optical characteristics depend on defects and the pretreatment of a material, so that they can be tuned and optimized for specific technological applications.

Magnetism and spintronics

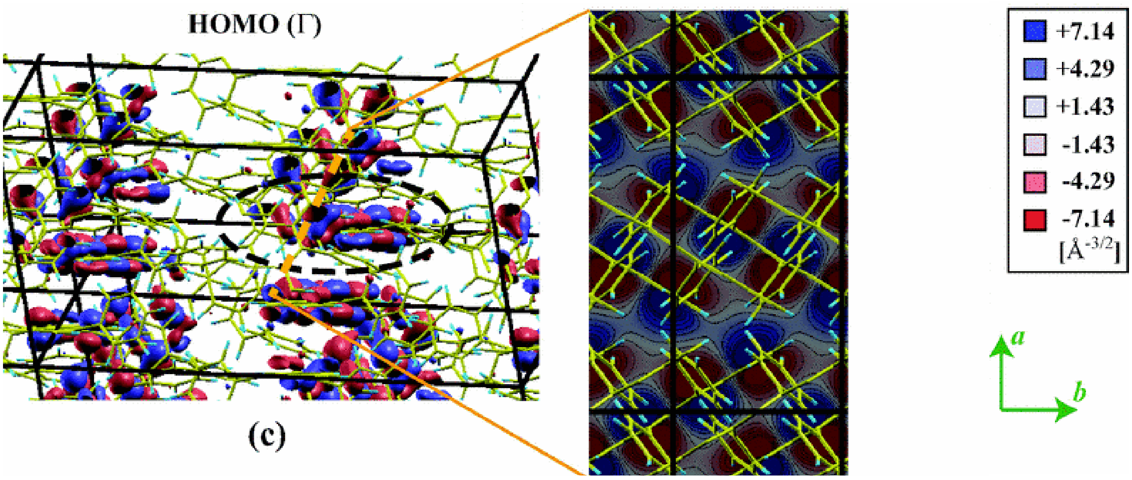
Compared to traditional electronic devices, whose functionality relies crucially on charge transport, spintronics constitutes a promising new concept where information is encoded in the electron spins. As these can be manipulated by external fields without physical transport, much faster switching times become possible, but many technical problems, such as dissipation due to the interaction of electrons with spin waves, remain unsolved so far. Building on our experience with ab initio many-body methods, we apply the same techniques to collective spin excitations in magnetic solids. In this way we obtain material-specific spin-wave dispersions in good agreement with experimental measurements, as well as line shapes and spectral functions. The results provide guidance on the choice of materials for spintronics applications and on the coupling of electrons with spin waves.



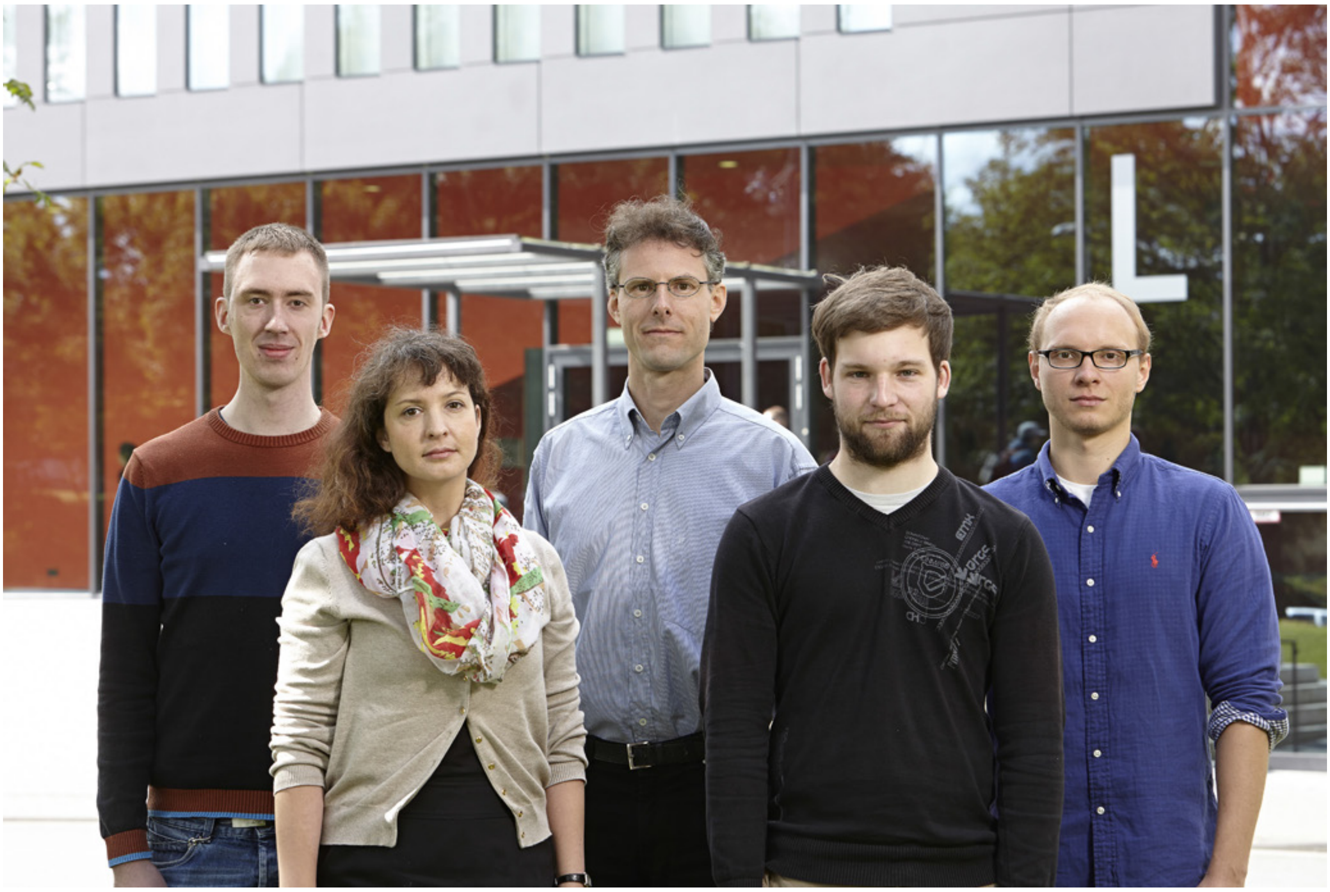
Calculated spin-wave dispersion of iron.

Method development

Modern ab initio methods, such as density-functional theory or many-body perturbation theory, are formally exact reformulations of quantum mechanics, but practical implementations require various approximations for electronic correlation and numerical efficiency that are often uncontrolled and may give rise to internal inconsistencies. As a proper understanding of these approximations is the key to reliable quantitative predictions, we investigate their performance by a combination of formal analysis, analytic models and highly converged calculations for selected test systems. The results are then used to improve the computational procedures for simulations of real materials. Significant effort also goes into the development of computer codes for efficient simulations of complex solids and into their extension to further spectroscopic quantities of interest for technological applications.



Wave function of the highest occupied molecular orbital in crystalline rubrene, an organic semiconductor.



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Methods

- Density-functional theory
- Many-body perturbation theory
- GW approximation
- Bethe-Salpeter equation
- Time-dependent density-functional theory

Theoretical Materials Physics
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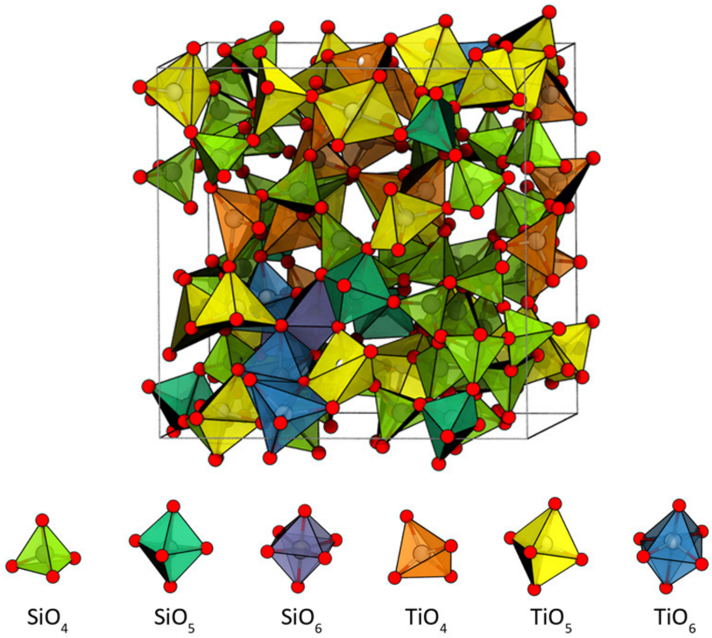
We employ density-functional theory and Green function methods in order to predict and understand a wide range of materials properties. For example, we are interested in atomic geometries, electronic and optical excitation spectra, phase transitions and electron transport properties. Solid surfaces, organic/inorganic interfaces, ferroelectric materials and biomimetic model complexes are the focus of our present research.

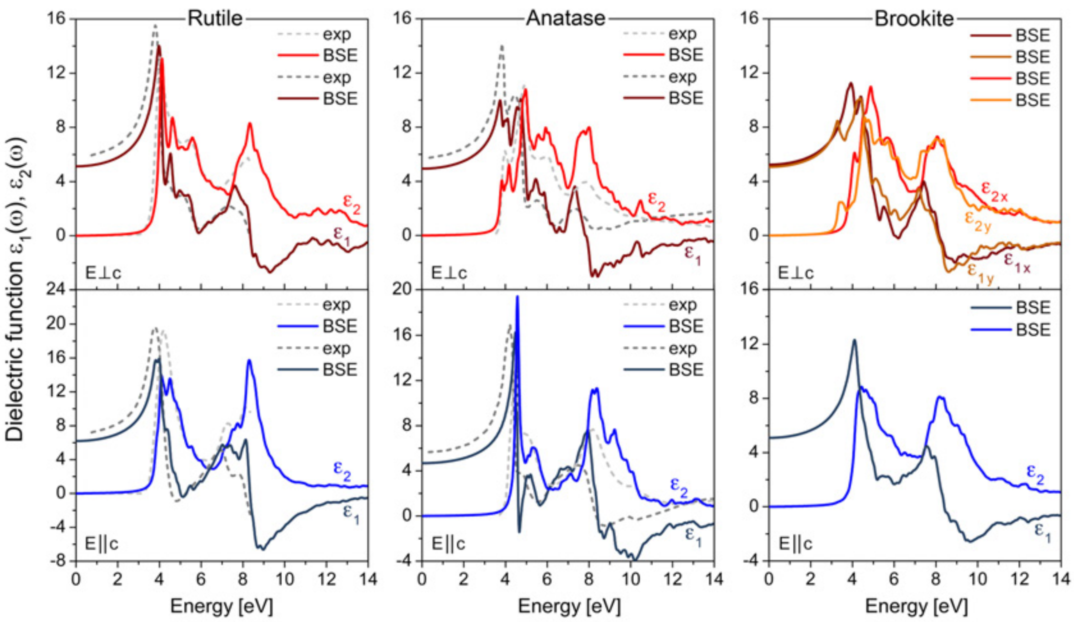
Ground-state properties

Ground-state total-energy calculations using density-functional theory (DFT) have grown into a powerful theoretical tool to gain a quantitative understanding of the physics and chemistry of complex molecular, liquid, and solid state systems. The pseudopotential approach provides an effective and reliable means for performing such calculations in a wide variety of poly-atomic systems, particularly together with a plane-wave basis and modern minimization algorithms for the variational determination of the ground state. In this approach only the chemically active valence electrons are dealt with explicitly. DFT pseudopotential calculations are performed in our group for a large variety of systems, ranging from bulk semiconductors such as silicon and gallium nitride, various oxides and ferroelectrics as well as molecular systems - presently in particular biomimetic copper complexes and organic semiconductors - to nanostructures such as superlattices, atomic-scale nanowires and interfaces.



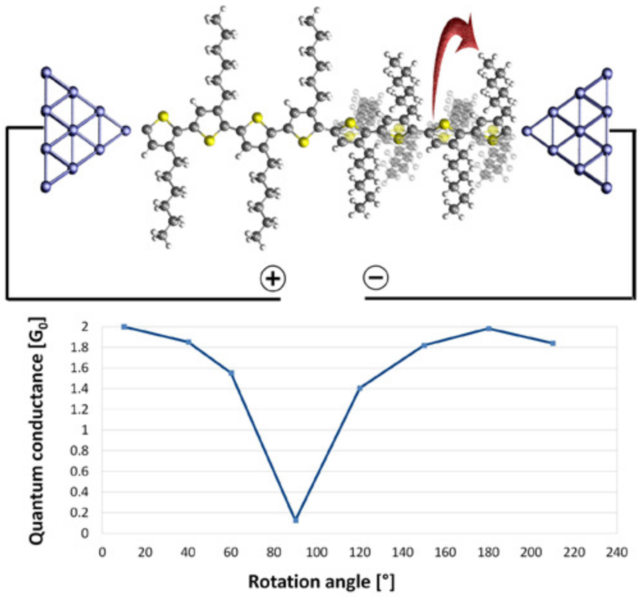
Calculated geometry of amorphous $Ti_{0.4}Si_{0.6}O_2$ in coordination polyhedra representation.

Spectroscopic signatures



TiO_2 dielectric function calculated on the BSE level of theory in comparison with measured data.

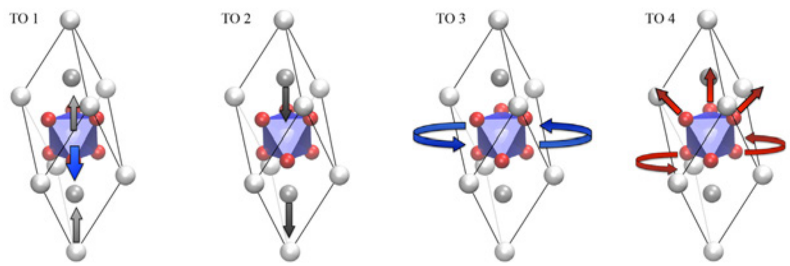
The calculation of excited states and their properties requires extensions to DFT. Accurate excitation energies may be obtained from propagator or Green function approaches. They start from the screening response of the electronic system after electronic or optical excitation. Accordingly, the dynamically screened or shielded Coulomb interaction W is the central quantity used in these methods. The excitation energies correspond to the poles of single- and two-particle Green functions that are obtained by means of many-body perturbation theory.



Molecular structure influence on the calculated quantum conductance of P3HT.

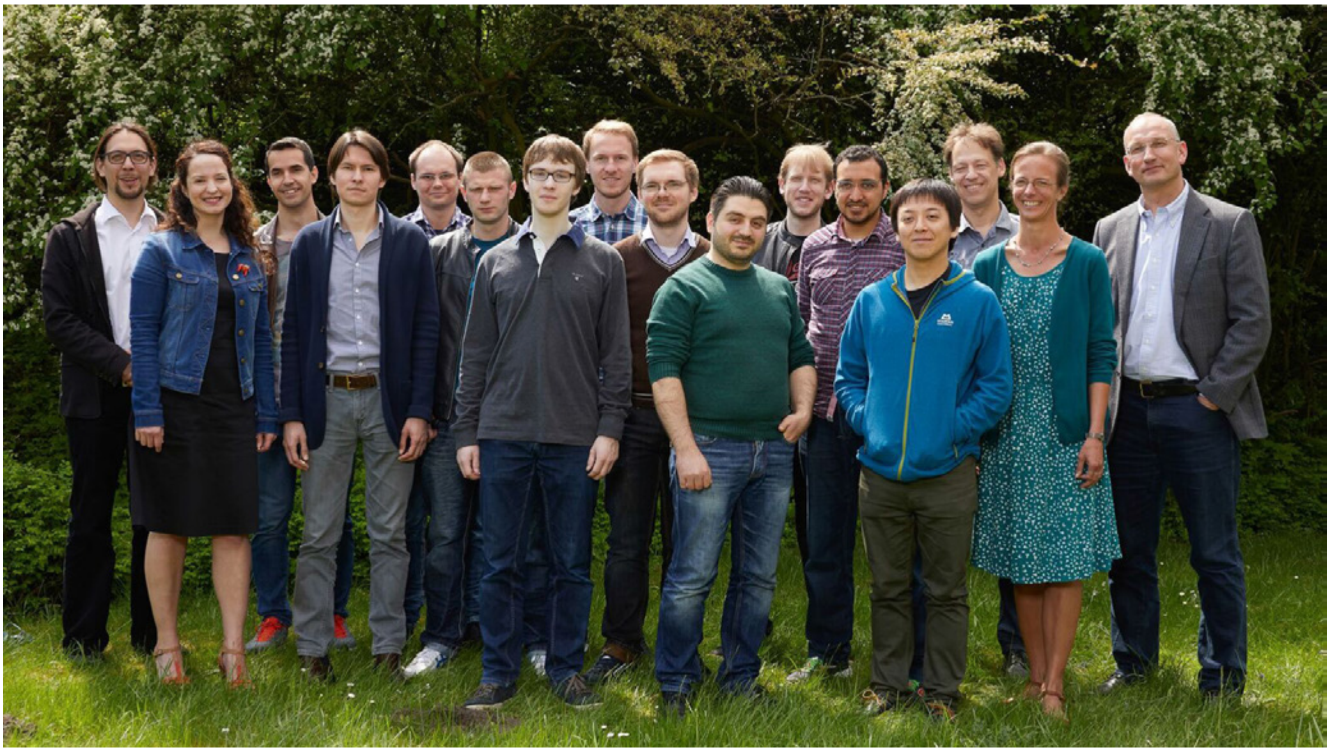
By evaluating the one-electron Green function G, single-particle excitations, e.g., ionization energies and electron affinities, are derived that can be measured in photoemission and inverse photoemission spectroscopies. Two-particle Green functions of the electronic system allow to access electron-hole pair energies and collective excitations, e.g., plasmons. In the practical implementation, we resort to approximations to describe the most relevant correlation mechanisms. In particular, our group uses Hedin's so-called GW approach to calculate electronic quasiparticle energies. The electron-hole interaction in optical excitations is accounted for by solving the Bethe-Salpeter equation (BSE) for the polarization function. Charge neutral molecular excitations are typically addressed using the linear-response approach to time-dependent DFT (TDDFT). Recent methodological work of our goup focusses on the gauge-including projector augmented plane wave approach to treat external magnetic fields, the calculation of electron paramagnetic resonance (EPR) as well as nuclear magnetic resonance (NMR) spectra and relativistic calculations including spin-orbit coupling that start from the Foldy-Wouthuysen transformed Dirac Hamiltonian. Electron transport properties are calculated using Green function methods and scattering techniques.

Ab-initio thermodynamics



Calculated lithium niobat phonon modes

For a deeper understanding of materials properties, the discovery of hidden chemical trends, the prediction and microscopic understanding of phase transitions and ultimately the design of materials with tailored properties it is indispensible to go beyond ground-state calculations at zero temperature and describe the materials at their operating temperatures. For an accurate description of finite-temperature materials properties, an accurate treatment of all entropic contributions such as electronic excitations, lattice vibrations and possible configurations is crucial. We use the frozen-phonon approach as well as density-functional perturbation theory to calculate phonon modes and phonon frequencies. Effects of anharmonicity are studied using ab-initio molecular dynamics. The results are used, e.g., for the exploration of phase transition mechanisms, the prediction of critical temperatures as well as for simulations of kinetics and energetics of chemical reactions.



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Theory of functional photonic structures
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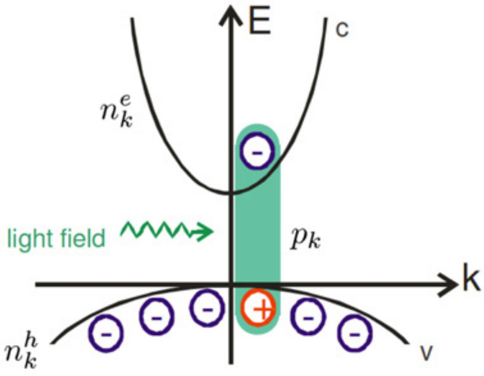
Nanostructured semiconductors nowadays play a crucial role in optoelectronics and photonics and have become indespensible in our everyday life. The optical properties of such systems are determined by complex excitations inside the material, the details of which can often not be understood with simple models.
In the Theory of Functional Photonic Structures group we develop microscopic theories, describing the nonlinear optical excitation dynamics of nanosystems down to ultrashort timescales. We study both systems based on crystalline inorganic semiconductors as well as organic molecular materials at the interface between physics and chemistry.
Together with experiments we obtain insight into microscopic physical mechanisms underlying the systems' optical properties. Beyond pure basic research, we also use our understanding of the nonlinear light-matter interaction to envision concepts for novel light manipulation schemes such as all-optical switches or quantum light sources.

Introduction

The scientific focus of our group is on the study of semiconducting and molecular nanostructures. These, for example, include semiconductor quantum wells and quantum dots, and different molecular systems at the nanometer scale. We have a strong expertise in developing microscopic quantum theories that accurately describe the interaction of (laser) light fields with the electronic many-particle system in these structures. Based on these theories, we study and 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 also combine these calculations with different electronic structure methods to calculate the confined electronic states inside the nanostructure. In most of our projects we work closely together with theoretical and experimental collaborators - locally, and all around the world - providing us with the right mix of expertise. Besides a fundamental understanding of the systems we study, an important aspect of our work also is to envision novel concepts that are of interest for future applications in optoelectronics and photonics.

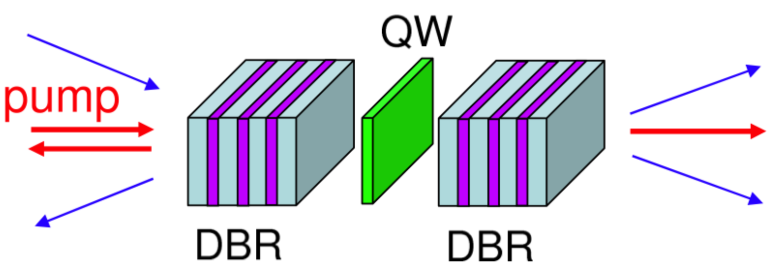
$$i\hbar\dot{\psi} = H\psi$$

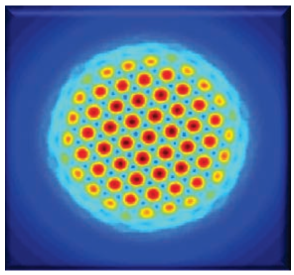


Nonlinear photonics of semiconductor nanostructures

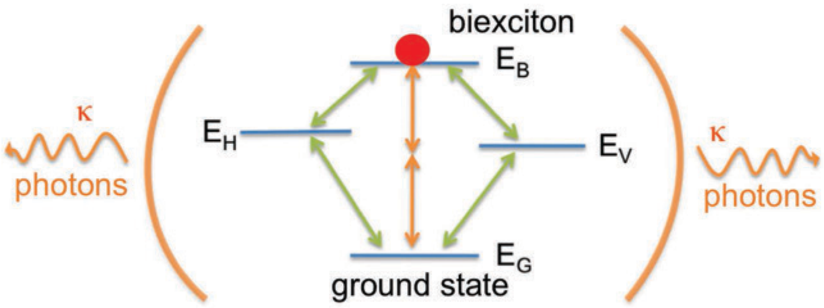
In the area of photonics, in addition to the design of the electronic states of a given nanostructure, we aim to also design the propagation of light through the system. We are particularly keen to study optical excitation schemes in which the system behavior can be controlled all-optically and in which complex many-particle interactions are at play and can be made use of.

Nonlinear polariton physics in semiconductor microcavities - In semiconductor microcavities, the strong coupling of the quantum-well exciton to a confined optical mode leads to the formation of new quasi-particles that are half light, half matter in nature. The peculiar properties of these particles (polaritons) can be used to supress unwanted and on the other hand harness desirable aspects in the nonlinear response of the system. For example, under resonant coherent cw laser excitation, spontaneous pattern formation can occur, which can be used for low-light-intensity all-optical switching. We also study off-resonant excitation with spatially structured laser fields, which provides us with a promising route to the realization of optically reconfigurable integrated circuits based on microcavity polaritons.





Left: planar semiconductor microcavity with optical excitation and read-out.
Right: spontaneous polariton pattern formed under cw pumping.



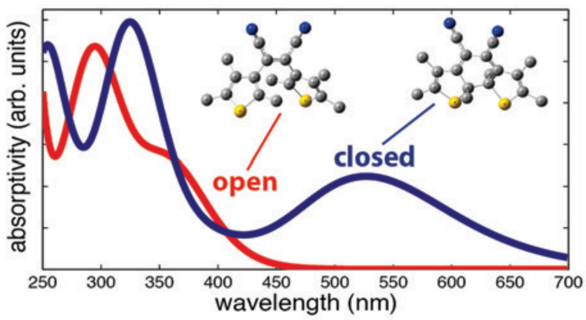
Sketch of electronic excitations of a semiconductor quantum dot inside an optical cavity. Indicated are the cascaded emission from the biexciton through the exciton levels and the direct two-photon emission.

Quantum optics with semiconductor quantum dots – Semiconductor quantum dots are one of the best controlled solid state systems that can be used as on-demand quantum-light source. Due to their atom-like discrete energy level spectrum they are often also referred to as artificial atoms. We investigate the optical properties of these nanometer scale systems with a focus on their use as emitters of single photons and pairs of polarization-entangled photons, which can be used for quantum communication purposes. The focus of our present studies lies on direct two-photon emission processes involving ground state and biexciton of the quantum dot. This process will be used to realize a single-photon source with optical control over polarization and frequency of the emitted photon. An optical cavity enhances the emission into the desired two-photon channel. Our theoretical calculations give us detailed insight into the coupled photon-exciton-biexciton dynamics and into quantum properties and statistics of the emitted light.

Molecular photophysics

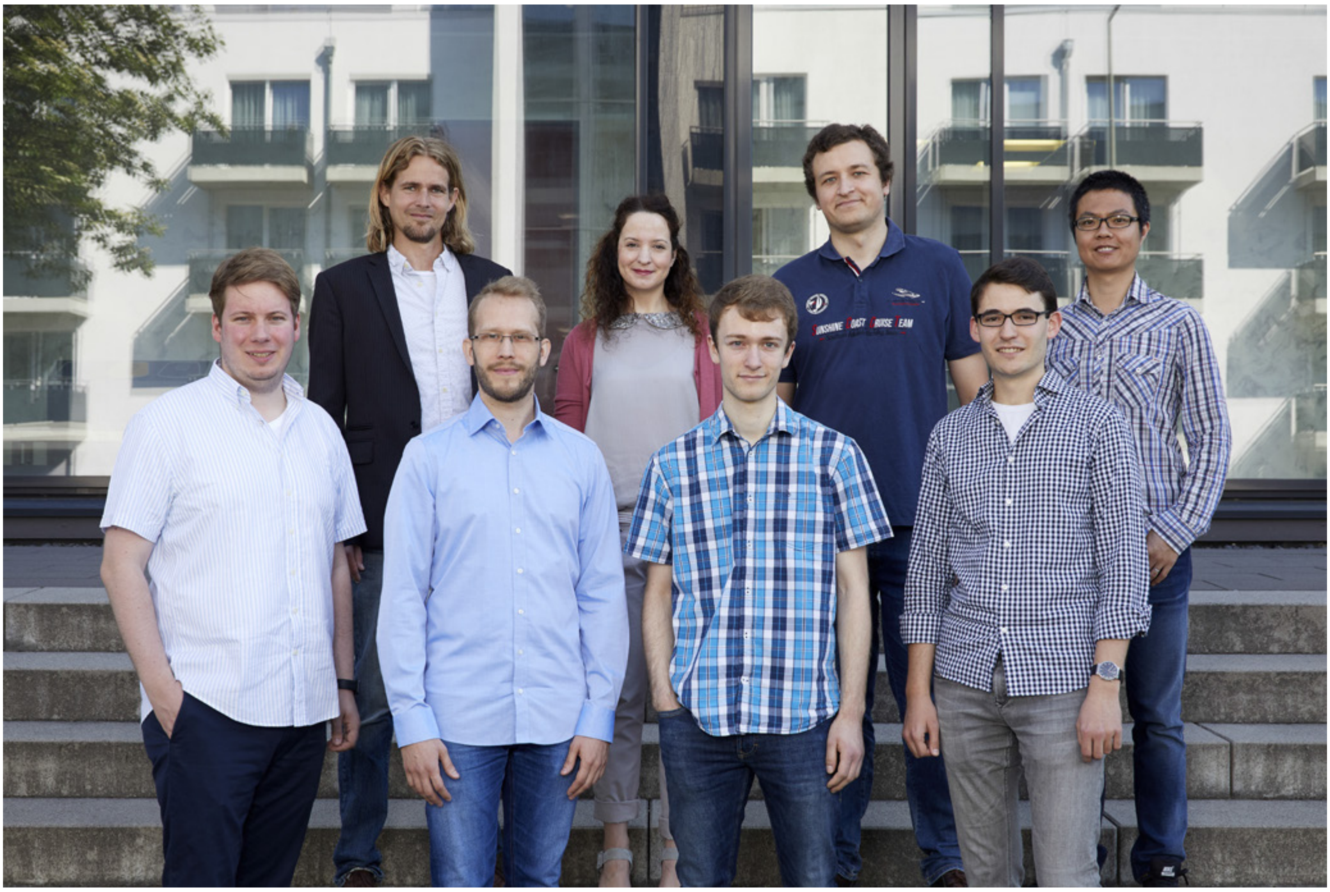
Over the past years, molecular materials and organic semiconductors have proven their potential for various applications in optoelectronics and photonics. Many of these materials possess desirable properties or even functionalities rooted in the complex nature of their molecular constituents that are not found elsewhere.

1. Molecular photo switches – In this area we investigate photochromic diarylethenes, molecules that can be optically switched between two stable ground-state conformers. In the visible spectral range these two forms show very different optical properties. Based on detailed quantum-chemical calculations we study electronic states and related optical properties and relaxation dynamics in the excited state manifold. The latter can be used to predict reaction times and quantum yields for a specific molecular compound. In the future, we plan to include these molecules into inorganic/organic hybrid systems, where the molecules serve as photoactive and photo-addressable components in the photonic structures.



Calculated absorption spectra of a photochromic diarylethene in its two stable ground state geometries. These molecules can be used for functionalization of photonic structures.

2. Organic semiconductors – We study the electronic and optical properties of semiconducting conjugated polymers. These materials combine the flexibility of plastics (easy to process, non-toxic, cheap) with desirable electronic and optical properties and are of interest for a large variety of applications in optoelectronics, photonics, and photovoltaics. We investigate these molecular systems using high-level quantum-chemical methods and develop models to study their nonlinear optical properties and excitation dynamics. Aspects in the focus of our present studies are polarons, photogeneration of charges, and exciton dynamics in molecular films.



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Methods

- Density-matrix theory based quantum-mechanical models of electronic excitations in nanostructures
- Ab-initio quantum-chemical methods for electronic states, excitations, and dynamics in molecular nanosystems
- Electromagnetic field simulations in simple photonic structures
-

Theoretical quantum optics

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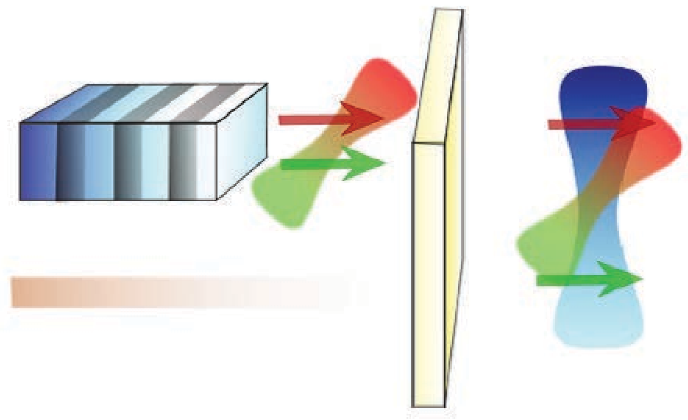
In general, photons are excellent information carriers because of their high speed, weak interaction with the environment, and available schemes that allow to manipulate their properties, create protocols of quantum cryptography and quantum teleportation, provide quantum computing and quantum information algorithms.
In the Theoretical Quantum Optics group we are working with different non-classical states of light: single photons, biphoton pairs, squeezed and bright squeezed vacuum states of light. We develop theoretical description of such states, we study their properties and correlations as well as investigate applications of such state of light for super sensitive linear and non-linear interferometry, for generation entangled states and single mode sources, for encoding information and light-matter interaction. We research such states of light in bulk optics and also in integrated systems.

Integrated two-and four-photon interference

The two-photon interference or Hong-Ou-Mandel (HOM) interference is well-known effect which takes place when two indistinguishable photons come at different ports of balanced beam splitter. The HOM interferometry is widely used to measure the degree of indistinguishability of photons and to overcome a time-resolution of detectors. For practical large-scale applications in quantum information processing free-space set-ups are not reliable because of the experimental complexity that is required to achieve and maintain a precise and stable adjustment between the elements and due to the significant size of such systems. However, due to their small size and high stability integrated quantum optical systems are very promising in this direction. We study the HOM interference in integrated LiNbO3 platform with indifused titanium atoms and integrated parametric-down-conversion (PDC) source. We investigate the properties of such interference, the possibility of creating spatial entanglement in such interferometer, generation of Bell states, influence of arising entanglement on the coincidence probability, different regimes of bunching photons: typical HOM dips (bunching) and singlet Bell states (antibunching).

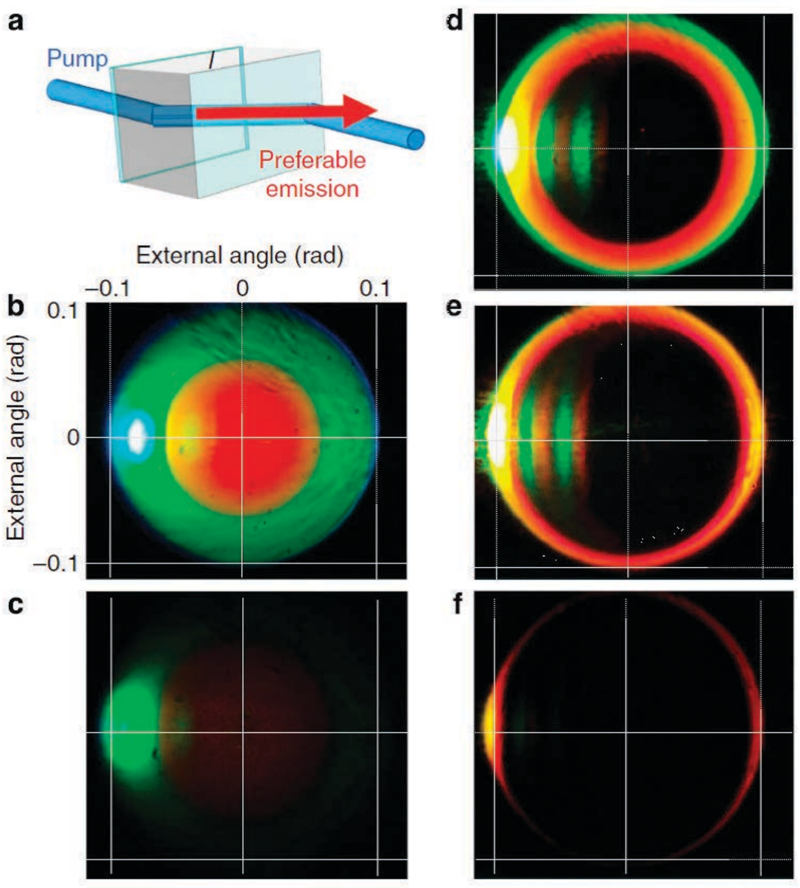


Generation of hyperentanglement. Two photons generated in a PDC process have frequency correlations. The creation of spatial entanglement between the photons leads to a hyperentangled structure which results in novel features in the coincidence probability

By increasing a number of photons situation becomes more complicated because the four-photon interference is more sensitive to mode structure of radiation. But simultaneously four-photon interference allowing achieves higher resolution and provides more precisely measurement in comparison with the two-photon interference. Moreover with increasing a number of photons the degree of entanglement in the system is also arise. The possibility to create different types of entanglement (spatial, frequency, polarization) and combine them leads to a hyperentangled structure which expand basis for encoding information and gives more possibilities for quantum information algorithms.

Bright squeezed vacuum (BSV) states of light

With increasing pump power significantly it is possible to create non-classical states of light with huge photon number per mode. Bright squeezed vacuum is characterized by high photon number correlations, strong correlations between frequency and space modes that make such state of light very promising for different applications in quantum information and quantum optics. The structure and properties of such states of light are different from the biphoton pairs regime and the perturbation theory methods do not work in such situation. That is why new methods and approaches are needed. We investigate spatial and frequency properties and arising strong correlations in BSV from the point of view of collective broadband (Schmidt) modes. We study the mode structure of radiation, dependence of the multiphoton correlations and the mode content with the parametric gain, walk-off effects, different schemes of BSV generation, high-order orbital angular momentum (OAM) in BSV and their strong correlations, etc. Also we study time-ordering effects in BSV which become crucial with increasing photon numbers. The time ordering effect means that local photon creation processes in nonlinear media must be ordered in time and manifest themselves, for example, in the broadening of the spectrum with increasing pump power.



Beamlike PDC along the pump spatial walk-off. The highest gain is achieved for emission along the pump Poynting vector, which inside the crystal is non-collinear to the wavevector (a). Snapshots with a photographic camera (b–f) show the spectra of high-gain PDC at different crystal orientations.

Non-linear SU(1,1) interferometry

A configuration with two non-linear mediums where PDC process takes place and dispersive medium between allows to create SU (1,1) non-linear interferometer. Such type of interferometer is very stable to the external losses and simultaneously very sensitive to the external phase of signal, idler or pump photons. Such properties make SU(1,1) interferometer very promising for measuring procedure. We study SU(1,1) interferometry in spatial and frequency domain with using biphoton pairs and BSV states in bulk optics and also in integrated platforms. We investigate the properties of such interferometer in the low and high gain regimes and the possibility of creation single mode source with huge photon number. Integrated single chip SU (1,1) interferometer is a challenging problem which promise a new possibilities in the interferometry.

Principle of the method of SU(1,1) interferometer. A broadband PDC pulse is generated in a strongly pumped nonlinear crystal; the PDC pulse spreads and chirps after propagation in a medium with group velocity dispersion (GVD); the spread and chirped PDC pulse is amplified in another crystal, using the same pump pulse. The frequency spectrum after the second crystal is narrower than that after the first one.

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- Daniel Possienke (technician)
- Simone Lange (team assistant)
- Jun.-Prof. Dr. Polina Sharapova

Integrated Quantum Optics
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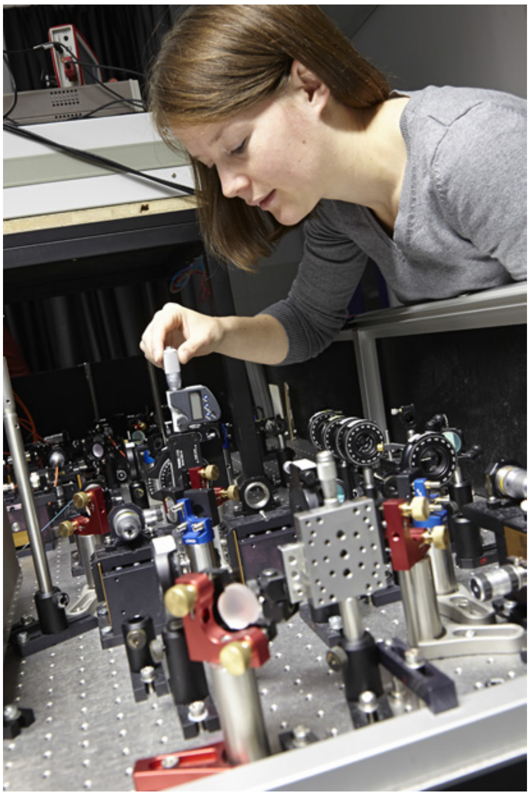
The integrated quantum optics group investigates new photonic setups for applications in quantum information processing, quantum communication, and fundamental questions of quantum theory. Our goal is, on the one hand, to develop quantum devices for practical applications, and on the other hand, to implement large photonic networks with a high complexity in terms of number of channels and sophisticated non-classical input states. To this end we explore the quantum character of light by studying particle-like as well as wave-like properties.

In our experiments we use tailored integrated optics, pulsed light, time-multiplexing and photon number resolving detectors. Our integrated optic devices reduce significantly the experimental effort for quantum light sources and quantum circuits with ensured high interferometric stability. Employing pulsed quantum light offers several benefits: within one quantum system different creation and detection events can be synchronized, quantum systems can be operated at high clock rates, and time-multiplexing can be used for resource efficient implementations. Furthermore, ultrafast pulsed quantum light features a rich temporal-spectral structure which is well suited for fundamental studies and high-dimensional information encoding.

Quantum networks

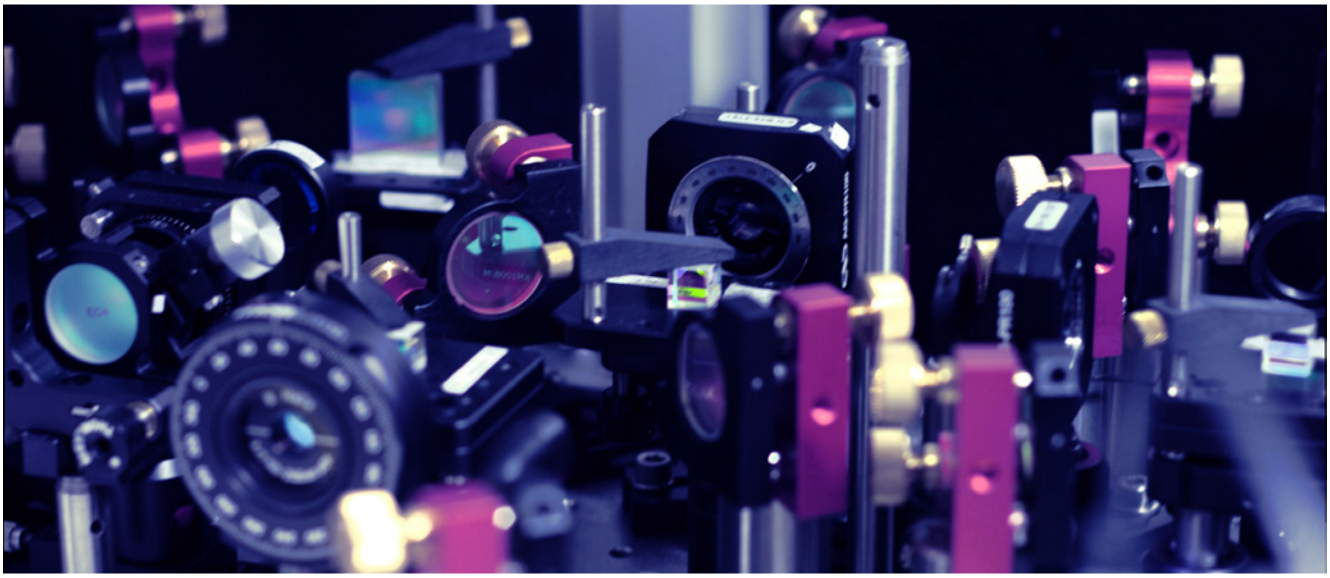


When aiming for the realisation of large-scale quantum networks, one soon realises that the demanding requirements on the different building blocks as well as the need for scalability limit the maximum size of practical systems. Integrated architectures provide an attractive solution to this problem, because they provide scalability, cost reduction and integrability into existing infrastructures that bulk architectures are not capable of. Our research along these lines is divided into complementary approaches, which concentrate on different aspects of large-scale networks.

We have recently realised a new tailored source of indistinguishable photon pairs at telecom wavelengths, based on KTP waveguide structures. Intrinsically, these photons are generated in multi-mode ultrafast pulses, which can serve as a high-dimensional basis for information encoding. In this context we developed two novel devices, which are capable of manipulating these quantum pulses: the quantum pulse gate and the quantum pulse shaper. In conjunction with our efficient, photon-number resolving detectors, which we characterise with highly sophisticated methods, we have at hand all building blocks to explore a novel degree of freedom for quantum information applications.

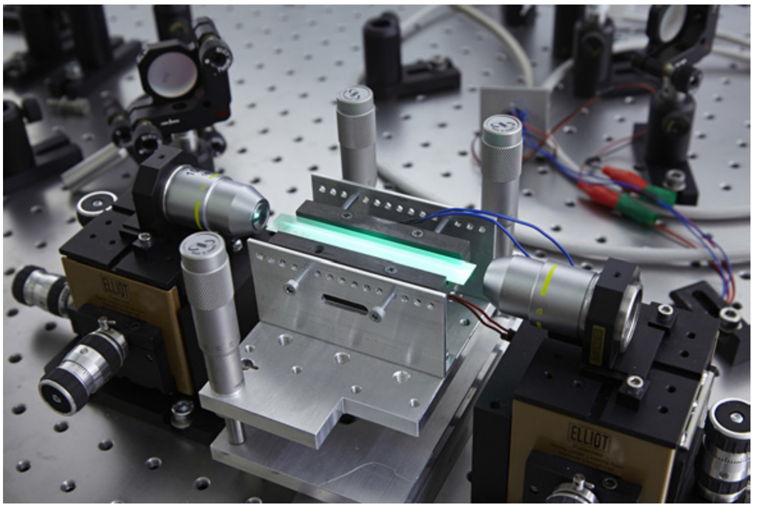
As an extension to our current studies, we also started to investigate integrated continuous variable quantum optics, and the benefits of integration incorporated into these schemes. Continuous variable quantum optics concentrates on the evaluation of field quadratures rather than photon statistics and promises cheaper detection, large bandwidths and ease of manipulation, when compared to the alternative single photon schemes.

Finally, we study quantum walks as means of flexible and efficient quantum simulation. Quantum walks describe the coherent propagation of quantum particles in a discrete environment and are a useful tool for performing quantum algorithms. We implemented a discrete-time quantum walk of photons in a resource efficient and versatile setup by deploying time-multiplexing and a clever fiber loop geometry, thus gaining intrinsic interferometric stability. We could already simulate disorder in the underlying environment leading to a trapping of the quantum walker as well as the walker's dynamic on various graph structures in one and two dimensions.



Integrated quantum devices

Integrated waveguiding structures in periodically poled $LiNbO_3$ and KTP are key components towards practical applications of quantum communication and information processing. Such devices with on-chip integrated multiple functionalities provide advantages in particular in terms of robustness and miniaturization.
An example of our recent work is the development of sophisticated single photon pair sources with narrow bandwidth and fiber compatibility exploiting a resonant waveguide structure. We also developed highly efficient two-color photon pair devices with integrated coupler structures on chip to demonstrate passive decoy-state quantum key distribution. Furthermore, we develop wavelength converters to bridge the large gap between UV and telecommunication wavelengths by exploiting parametric conversion in KTP waveguide.
Current research activities concentrate towards fully monolithic integration of photon pair sources with additional functional elements for quantum state manipulation. Examples are functional quantum optical circuits with polarization converters and interferometer, integrated sources of polarization entangled photon pairs, and the fully integrated generation of not only photon pairs, but photon triplets. Another activity focuses on the monolithic integration of electrooptic modulators and switches for fine tuning and state manipulation.

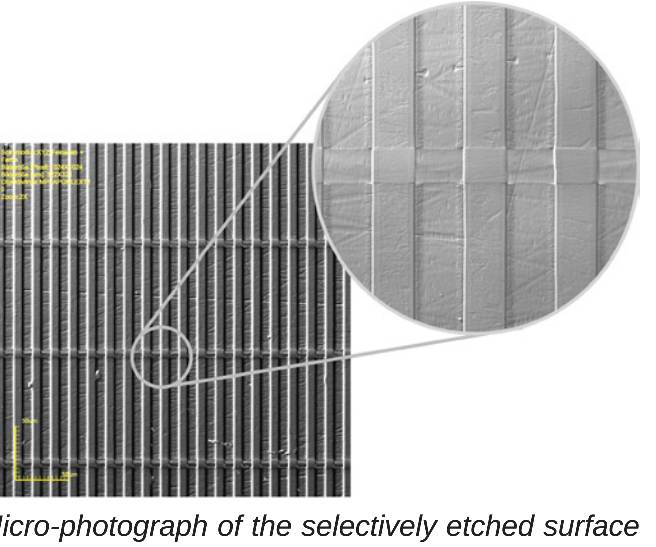


Waveguide device for photon pair generation

Technology

Ferroelectric domain micro-gratings in $\chi^{(2)}$ nonlinear optical waveguides are a genuine means for quasi-phase matching of parametric frequency conversion devices for integrated quantum optics. For the fabrication of such micro-domain gratings we have developed advanced field assisted poling methods with periods as short as 4 µm in ferroelectric $LiNbO_3$-waveguides. Recently, we have also successfully demonstrated short period poling Rb-ion exchanged KTP-waveguides. Due to its ionic conductivity KTP requires a special optical monitoring technique to control the poling process.

To improve the coupling efficiency to single mode fibres and the efficiency of nonlinear optical frequency conversion, we are currently working on the development of the first buried Rb-exchanged channel waveguides in KTP. Their symmetrized mode intensity distributions allow to improve the overlap of coupling modes.



Micro-photograph of the selectively etched surface of a periodically poled Rb:KTP-waveguide

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- Kerstin Falke (team assistant)
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Equipment

- several fully equipped quantum optics laboratories
- ps/fs laser sources from visible to telecom
- complex pulse characterization and shaping instrumentation
- single photon avalanche detectors from UV to telecom
- superconducting nanowire single photon detectors
- high resolution, single-photon sensitive spectroscopy
- clean-room fabrication facilities for $LiNbO_3$ and KTP waveguide devices
- ion-assisted e-beam evaporation machine for customized dielectric coatings
- facilities for linear and nonlinear waveguide device characterization and assembling

High Frequency Electronics
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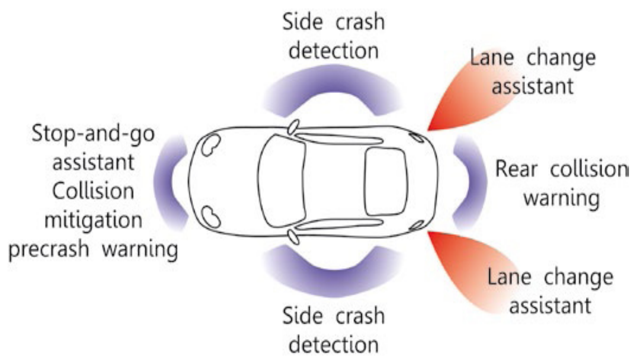
The High-Frequency Electronics group is mainly focused on the design of monolithically integrated circuits for applications in the high frequency domain, currently in particular for optical communications and sensorics.
Commercial standard software tools such as Cadence Design Framework and Agilent Advanced 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 PIDEA project the group has worked on a 24 GHz narrow band FM-CW radar system in Si CMOS technology for automotive and industrial use. DFG-funded projects targeted integrated active sensors for electromagnetic near field scanners and 110 Gbit/s decision feedback equalizers for the optical Ethernet. A 160 Gbit/s Mux is under development in a current DFG-project. In the recently started Collaborative Research Center TRR142, the group contributes high-speed electronic circuits for quantum mechanical experiments.

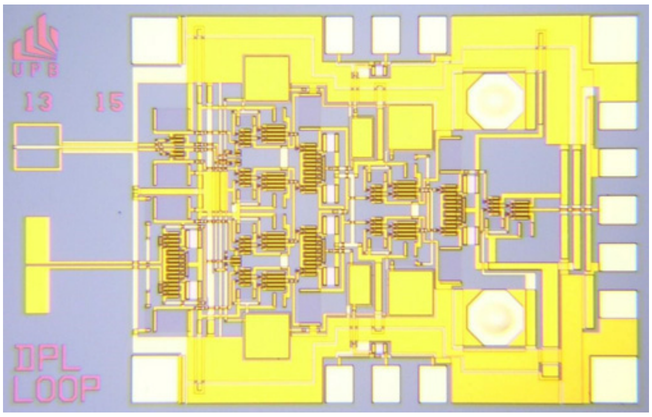
24 GHz Car Radar

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. In the European PIDEA project EMCPack FASMZS, managed by Fraunhofer ENAS/ASE, Paderborn, and Infineon Technologies AG, Munich, University of Paderborn collaborated with Hella KGaA Hueck & Co, Lippstadt and InnoSenT GmbH, Donnersdorf. In the development of a 24 GHz FM-CW radar for multiple uses in the car as illustrated above. Several ASICs have been developed by Paderborn University in close cooperation with Infineon. The chips were fabricated in Infineon's standard 0.13 µm CMOS technology with 6 Cu layers and 1 Al pad top level.



Application of Short Range Radar in Cars

Electric magnetic field sensors



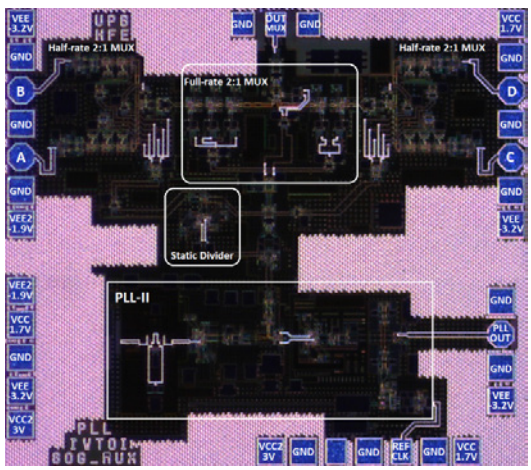
Magnetic/Electric Field Double Probe

Near-field measurements of PCBs and large-scale integrated circuits are gathering increasing interest for a better understanding of EM field distribution and respective EMC issues from the very beginning of the design process. Due to fine geometries of today's PCBs or even ICs, small field probes exhibiting high spatial resolution are of interest. Funded by DFG, a promising approach was used to obtain highly resolved field data with increased sensitivity by miniature probes including active circuitry. The figure exemplifies a GaAs based magnetic loop and electric dipole double probe integrated with switchable matched common source and common gate broad band preamplifiers.

High-Speed Data Communication

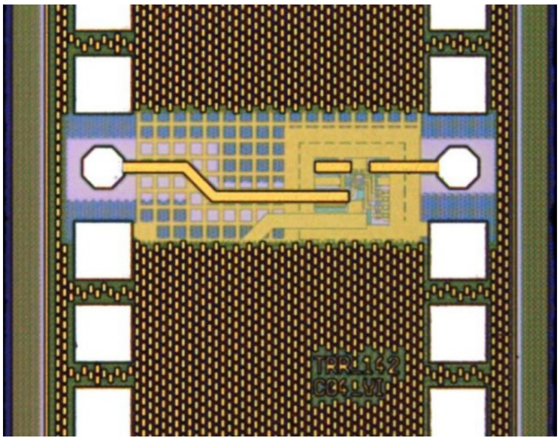
In optical high speed communication systems, insufficient receiver bandwidth, Chromatic Dispersion (CD) and Polarization mode dispersion (PMD) result in Intersymbol Interference (ISI) in the received signal. Besides linear FIR filters, nonlinear Decision Feedback Equalizers (DFE) have proven to be an effective method to compensate ISI. Based on a 0.13 µm SiGe HBT technology by IHP Frankfurt Oder, Germany, test circuits operating up to 110 Gbit/s input data rate have been demonstrated.

The DFG funded project has been continued by the development of 160 Gbit/s multiplexers, again in SiGe-HBT technology. The depicted 4:1 multiplexer comprises 3 cascaded 2:1 multiplexer stages and an on-chip PLL for high-speed clock generation.

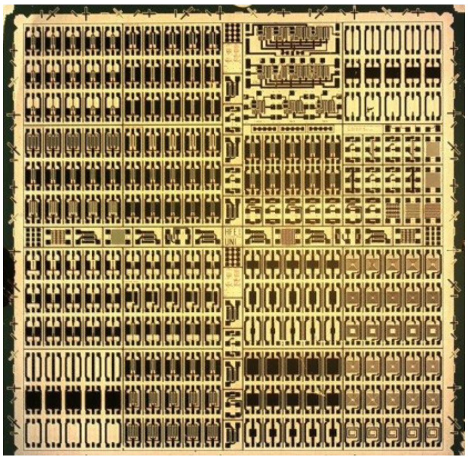


160 Gbit/s 2:1Multiplexer

Pico-second Pulse generator for Quantum Physics

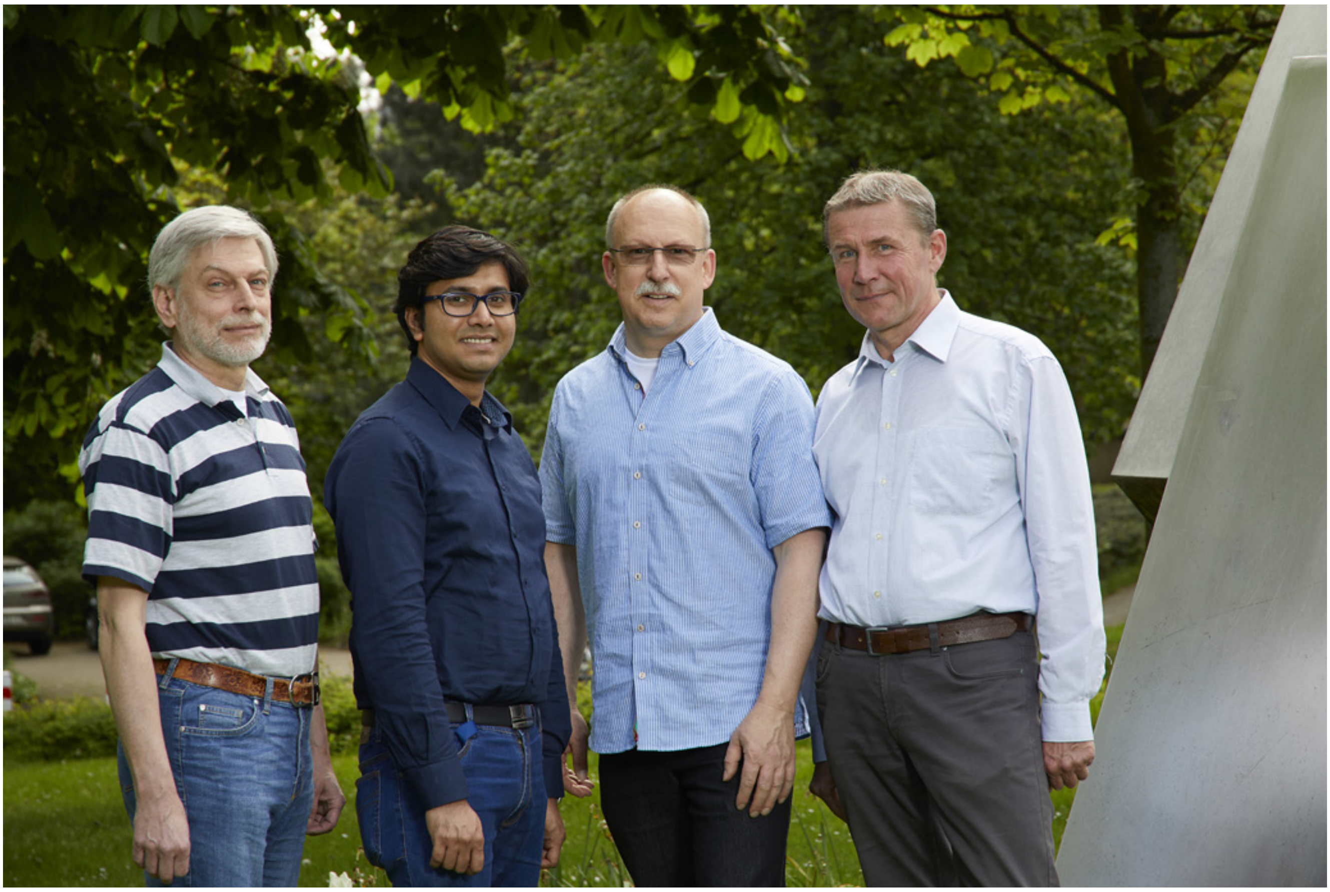

Pico Second Pulse Generator

In the frame of the DFG funded TRR 142 “Tailored Nonlinear Photonics”, pico-second pulse generating integrated circuits based on the 130nm SiGe:C BiCMOS technology by IHP Frankfurt Oder, Germany, were designed combining CMOS with high frequency heterojunction bipolar transistors. These circuits can be triggered using slower nanosecond edge pulse input. 15 ps rise time and 3 ps pulse width has been achieved in such circuits. These circuits also allow for pulse width tenability and amplitude control. Currently, such chips are being used to perform ultrafast coherent phase control experiments in quantum dots.


RF Test Field

Flexible RF Electronics for Communication

In the recently established DFG Priority Program FFlex-Com, University Paderborn collaborates with University Leipzig, Germany, in the development of basic analogue and digital circuit blocks for flexible communication electronics based on amorphous ZnO. The adjacent micrograph represents the RF test field, which allows high-frequency measurements and modelling of active devices, in particular ZnO based JFETs, as well as of passive components, such as spiral inductors, MIM capacitors, contacts chains, and cross-over structures.



Group Members

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- Dipl.-Phys. Frank Grotjahn
- Dr. Amlan Mukherjee
- Prof. Dr.-Ing. Andreas Thiede

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

Ultrafast Nanophotonics
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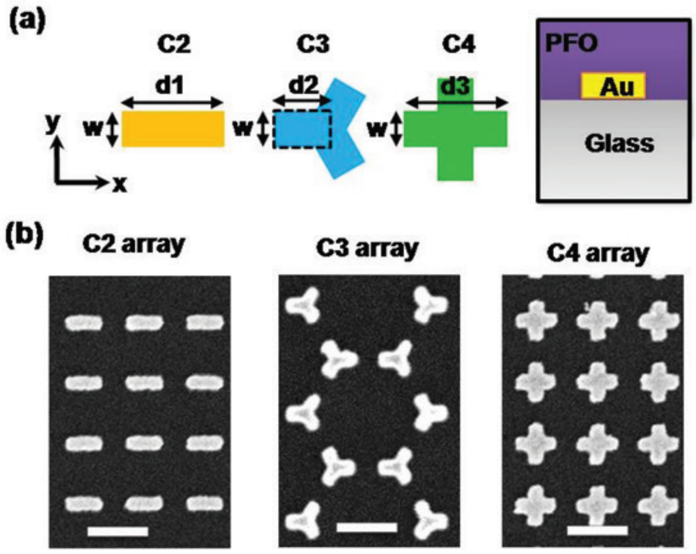
The Ultrafast Nanophotonics group at the University of Paderborn focuses its research on optical properties of artificial nanostructured material systems. Modern nanotechnology opens the possibility to manipulate the arrangement and structure of natural materials down to the nanoscale to sizes comparable to the optical wavelength. This freedom allows a direct engineering of the optical material properties that can be utilized for new classes 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 linear and nonlinear spectroscopy is the key for understanding the underlying excitation processes in these materials that lead to the desired functionality and potentially to highly compact and ultrafast optical devices.

Novel optical material concepts and design methods

The availability of optical materials with user-defined optical properties that would fulfill perfectly the requirements for applications are highly desired in the photonics industry. The lack of such materials limits the 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 sizes well below the optical wavelength. Such artificial 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 and dielectric nanostructures for the visible and near-infrared wavelength domain. In combination with newly developed design methodologies for even the nonlinear optical properties such an approach opens the possibility to obtain new functionalities for optical elements or even allow the realization of astonishing nonlinear optical processes. Topological phase effects by nanostructured materials have the advantage that nearly arbitrary phase profiles can be obtained for manipulating the propagation of a light field. Examples from our group include anomalous beam steering, dual-polarity lenses that are switchable from focusing to defocusing, and high resolution three-dimensional holography.

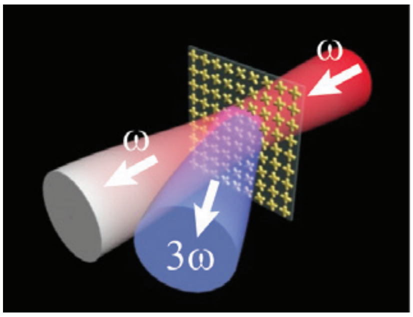


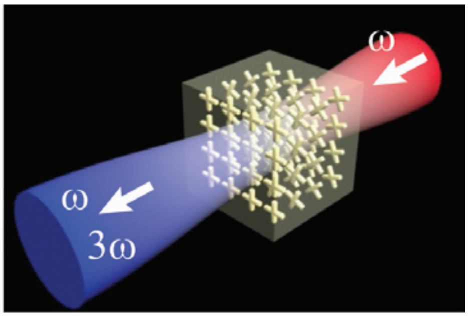
Metamaterial with desired symmetries for nonlinear optics

Realization of 3D holograms

Plasmonic devices for strong light-matter-interaction

Active photonic devices require a strong interaction of light with matter that can lead to nonlinear optical effects. Nevertheless, such nonlinear optical processes are in general weak and limit the functionality for real applications. In particular phase matching conditions have to be fulfilled to increase the efficiency along the propagation distance. Plasmonic nanostructures and nano-

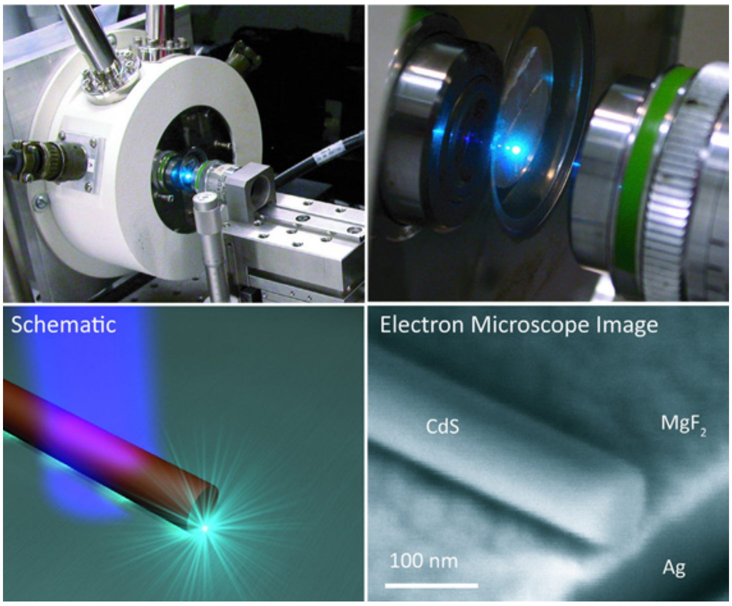




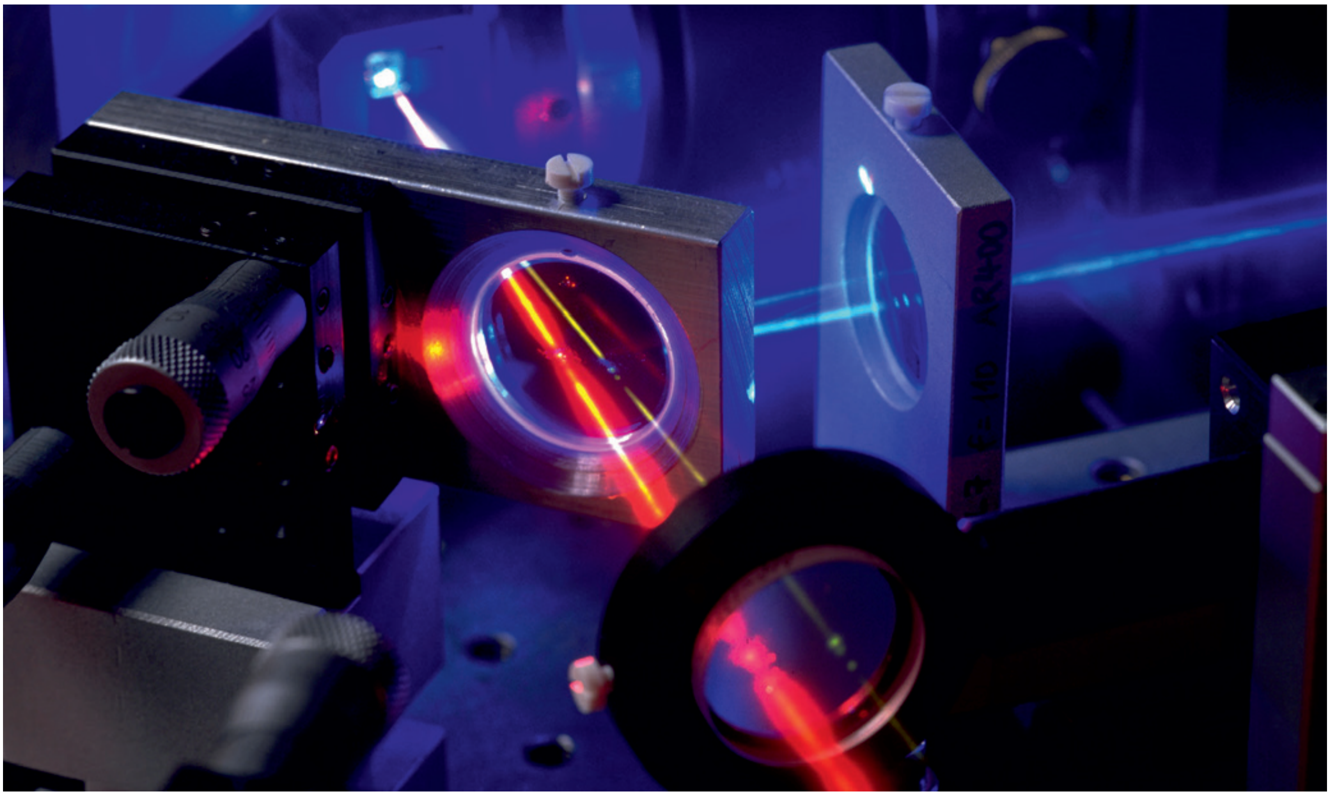
Nonlinear phase control and perfect phase matching for THG by Metamaterials antennas show a very strong light-matter-interaction and can lead in addition to a field enhancement in their proximity. Hence, they might be well suited for nonlinear optical processes. Recently, we demonstrated that even a tailoring of the nonlinear phase can be obtained by such nanostructured.

Ultra-small light sources

Many optical applications require small and highly efficient optical light sources. In particular quantum optical and on-chip devices would greatly profit from ultra-small sources. However, the efficiency of conventional light emitters is in general extremely poor. Our research activities in the field of ultra-small light sources are therefore focused mainly on strategies of enhancing the emission efficiency by directly modifying the emission 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. We employ 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.



Plasmonic Nanolaser made of CdS with light emission at wavelength of 490 nm



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- M. Sc. Bernhard Johannes Reineke
- M. Sc. Christian Schlickriede
- M. Sc. Florian Spreyer
- Dipl.-Phys. Felicitas Walter
- Andreas Herbst (technician)
- 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 and polarization sensitive spectroscopy for VIS and NIR

Nanostructure Optoelectronics
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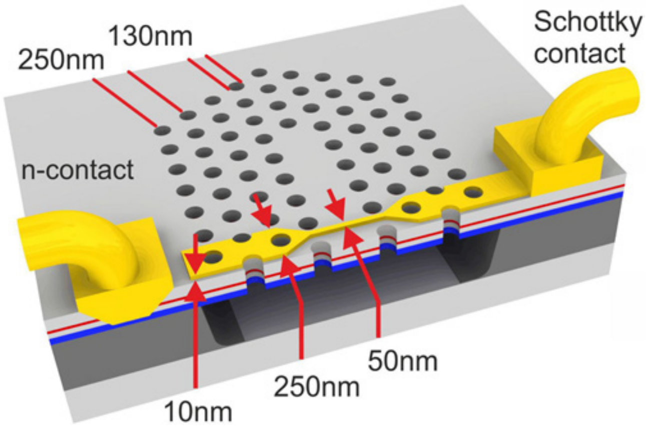
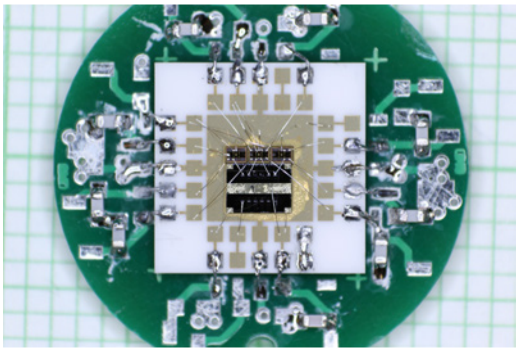
The research activities of the nanostructure optoelectronics group are focused on the physics and technology of semiconductor nanostructures and on the development and application of advanced optical analytics.
Our work on semiconductor nanostructures is concentrated on the preparation and investigation of single quantum systems, their controlled manipulation and functionalization on the level of single electrons, excitons or photons. This research field falls into the area of solid-state based quantum technology, in which the coherent optoelectronic control of single quantum systems and nonlinear interactions are of fundamental importance.
In the field of optical analytics we are focused on fs-nonlinear confocal microscopy and Raman imaging. Applied to semiconductors and nonlinear materials like ferroelectrics, those methods provide sub-μm spatial resolution and contrast mechanisms, which are inaccessible by linear optical microscopy.

Coherent optoelectronics with single quantum dots

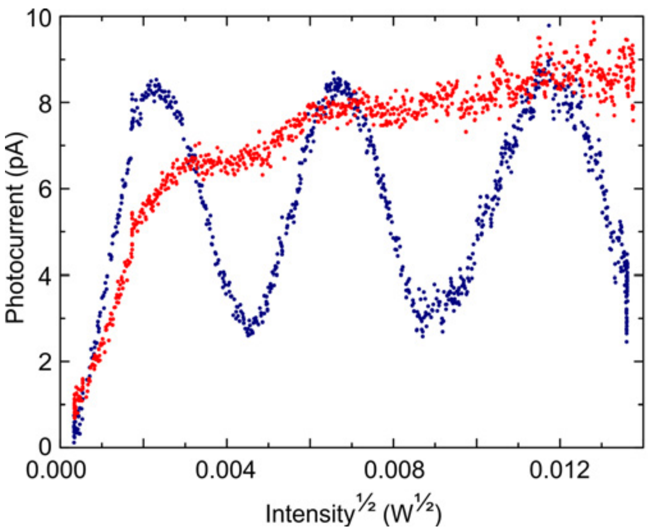
Semiconductor quantum dots (QDs) are artificial atoms contained in a host crystal. By resonant optical excitation with tunable laser fields it is possible to generate or annihilate excitons in the ground state of a QD. With ps laser excitation it becomes feasible to control excitons fast and efficiently in a defined way. Under those conditions, an exciton can be described as a quantum bit, which can be coherently manipulated in amplitude and phase. For our research we use self-assembled InAs/GaAs or InAs/InP QDs. 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 resonant spectroscopy we have been able to demonstrate Rabi-oscillations of exciton qubits on ps time scales. Engineered quantum dot photodiodes allow for quantitative readout of the occupancy of single quantum systems by photocurrent detection. Using ps electronics we are able to implement coherent optoelectronic state manipulations via transient Stark shifts of the exciton energy. In the focus of our current interests are further the application of nonlinear optical concepts as route towards highly controlled single photon emission- Our research activities in those areas are funded by the DFG via the TRR142 and by the BMBF "Q.com" program. The ongoing activities are designed to contribute to the new fields of coherent optoelectronics and quantum communication.



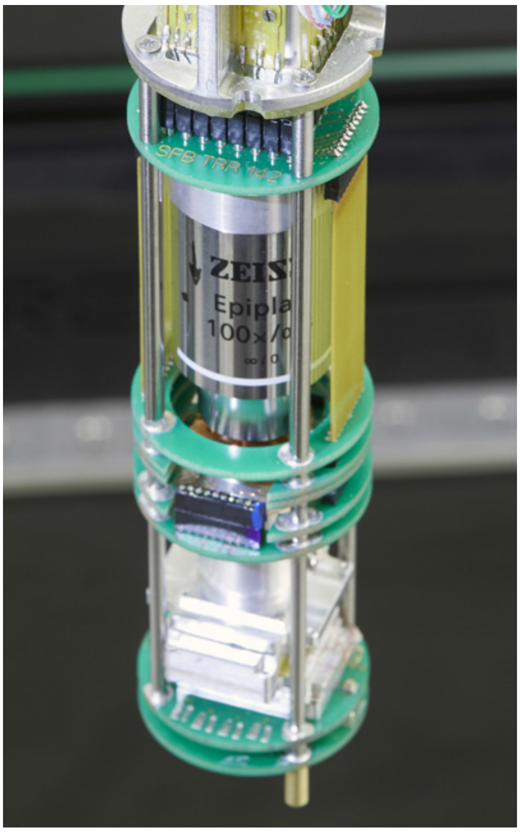
Schematic view of an electrically contacted microcavity



Single QD photodiodes with ultrafast electronic driver chips



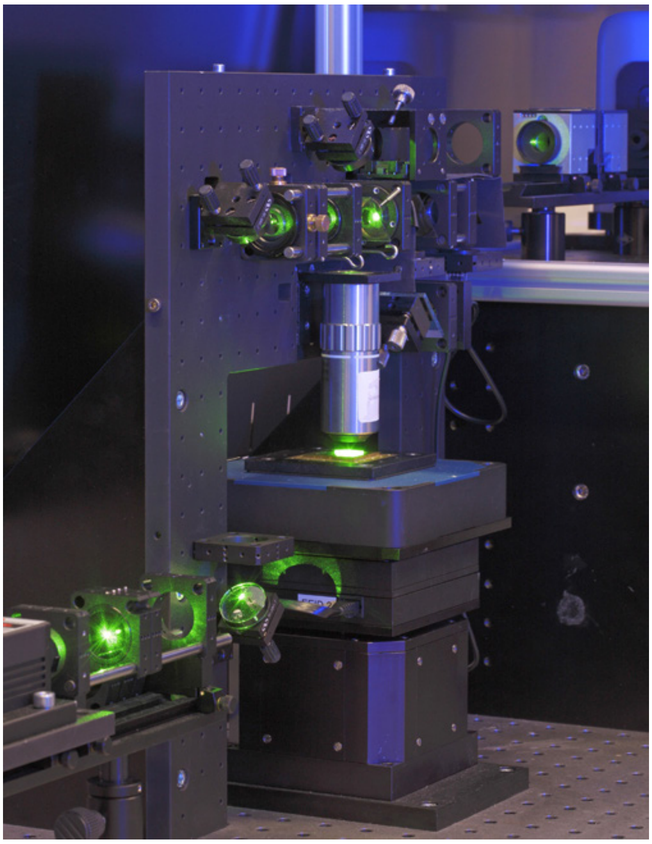
QD Rabi oscillations (blue) and electrically chirped rapid adiabatic passage (red)



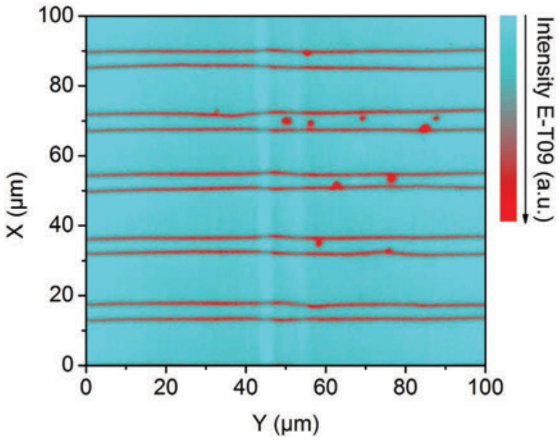
Tail part of a low temperature microscope

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.

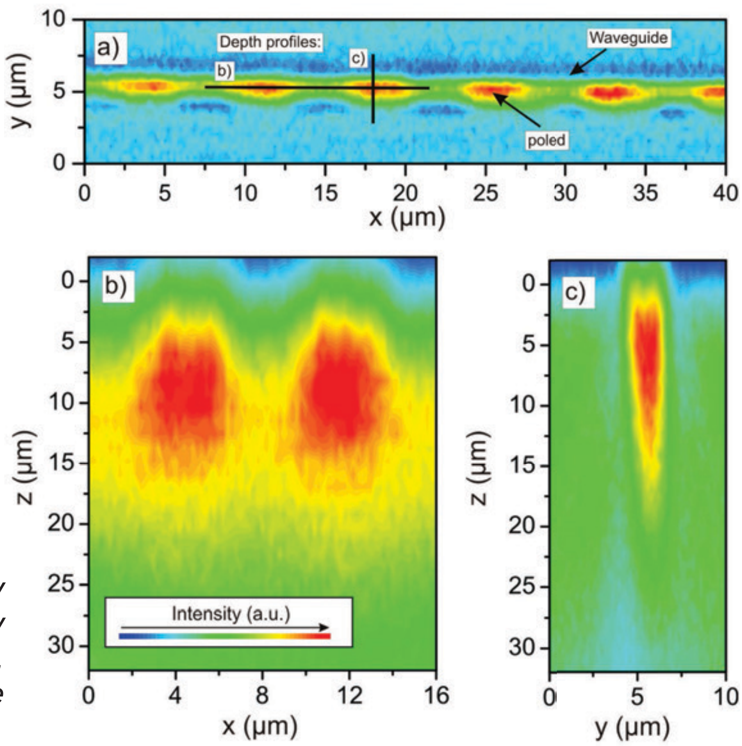
Second-harmonic imaging microscopy is applied to obtain images of ferroelectric domain boundaries in periodically poled $LiNbO_3$ and KTP structures. Performed in a confocal mode, with fs-laser sources and single photon detectors, this method provides tomographic images of the domain boundaries by scanning the specimen with respect to a fixed laser focus. Raman imaging, also performed in a confocal mode, is 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 dopants and extended defects, Raman spectroscopy is also a powerful tool to detect and analyse defects and impurities in integrated optical circuits for quantum-optical applications. The research activities in those areas are funded by the DFG via the TRR142.



Confocal Raman microscopy



Confocal Raman-image of periodically poled $LiNbO_3$ (domain boundaries: red)



Tomography of a periodically poled waveguide obtained by second harmonic microscopy. Different cross sections are shown in a), b) and c)

Group Members

- Dr. Gerhard Berth
- M. Sc. Björn Jonas
- B. Sc. Sebastian Krehs
- B. Sc. Peter Mackwitz
- Dr. Amlan Mukherjee
- M. Sc. Michael Rüsing
- M. Sc. Kevin Sträter
- M. Sc. Alex Widhalm
- Joshua Bockheim (apprentice)
- Selim Sayin (apprentice)
- Dipl.-Ing. (FH) Reiner Schneider (technician)
- Heike Degler (team Assistant)
- Prof. Dr. Artur Zrenner

Equipment

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

Facilities

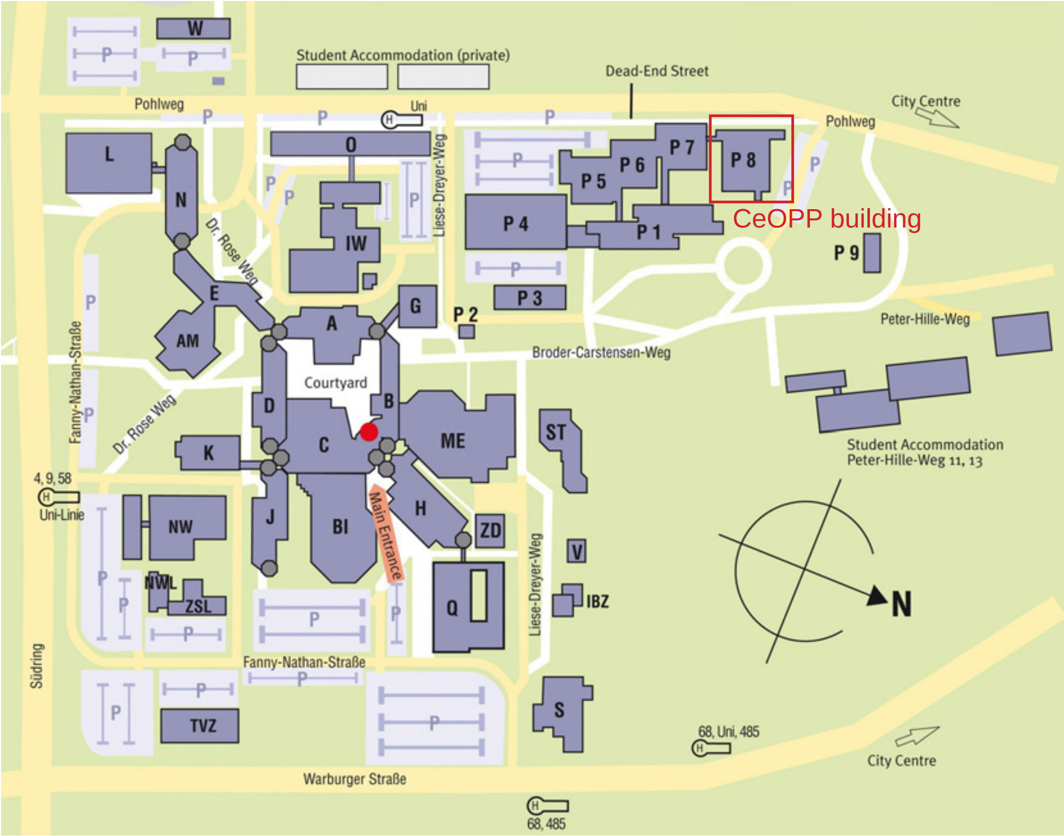
CeOPP Building

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

Special Equipment

- Optical Analysis
- Optical Data Transmission
- Bit Failure Analysis
- E-beam and optical lithography
- Nanotechnology
- Diffusion, Oxidation
- Rapid Thermal Processing (RTA/RTP)
- Evaporation and Sputtering
- Molecular Beam Epitaxy
- Laser Scanning Microscopy
- Low Pressure Chemical Vapor Deposition
- Plasma Enhanced CVD
- Reactive Ion Etching (RIE, PE)
- Advanced Silicon Etching (ICP-RIE)
- X-Ray Diffraction
- Scanning Electron Microscopy
- Atomic Force Microscopy
- Vaccuum STM
- Transmission Electron Microscopy
- Confocal Microscopy
- Microprobe x-Ray Analysis
- Optical Nearfield Microscopy
- Ellipsometry
- Optical Spectroscopy
- Picosecond/Femtosecond Spectroscopy
- Infrared Spectroscopy
- UV Spectroscopy
- Microoptics
- Microanalysis
- 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
- Microelectronics
- Micromechanics

Directions


Student Accommodation (private)
Dead-End Street
Pohlweg
Uni
City Centre
CeOPP building
P 8
P 7
P 6
P 5
P 4
P 1
P 9
P 3
P 2
Liese-Dreyer-Weg
Dr. Rose Weg
Peter-Hille-Weg
Broder-Carstensen-Weg
Courtyard
Main Entrance
Student Accommodation
Peter-Hille-Weg 11, 13
Fanny-Nathan-Straße
4, 9, 58
Uni-Linie
Südring
68, Uni, 485
Warburger Straße
68, 485
N
W
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N
O
IW
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AM
A
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Bielefeld
Detmold
Fürstenallee
ZM1
Zukunfts-meile
Neuhäuser Straße
Fürstenweg
Detmolder Straße
Ostring
Berliner Ring
Heinz-Nixdorf-Ring
Rathenaustraße
Paderborn Centre
Driburger Straße
Ludwigsfelder Ring
To the A2
Exit "Paderborn Zentrum"
Bahnhofstraße
Main Train Station
Borchener Straße
Husener Straße
Pohlweg
Warburger Straße
Campus
Höxter
Exit "Universität"
A33
B 64
Südring
Sport
B 68
Technology Park
Exit "Universität"
University GolfClub
Kassel
To the A44

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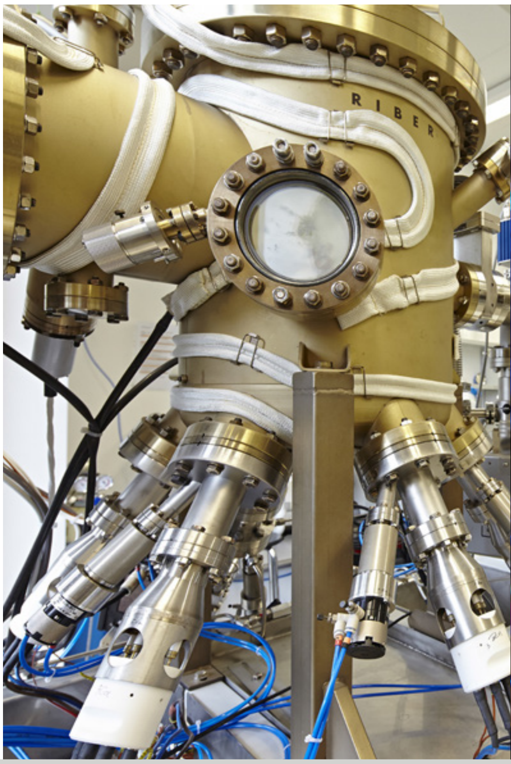
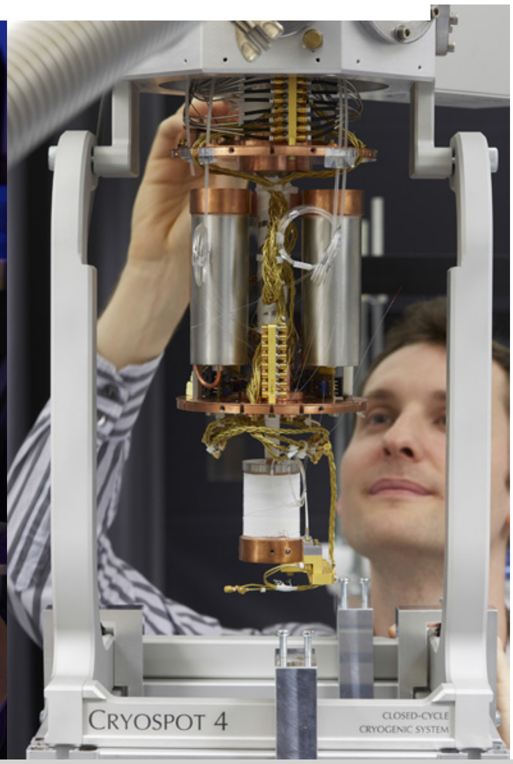
Die Universität der Informationsgesellschaft





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