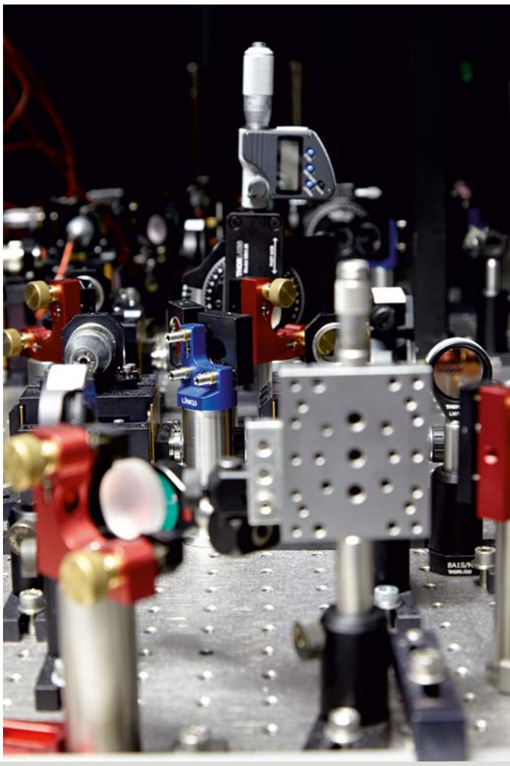
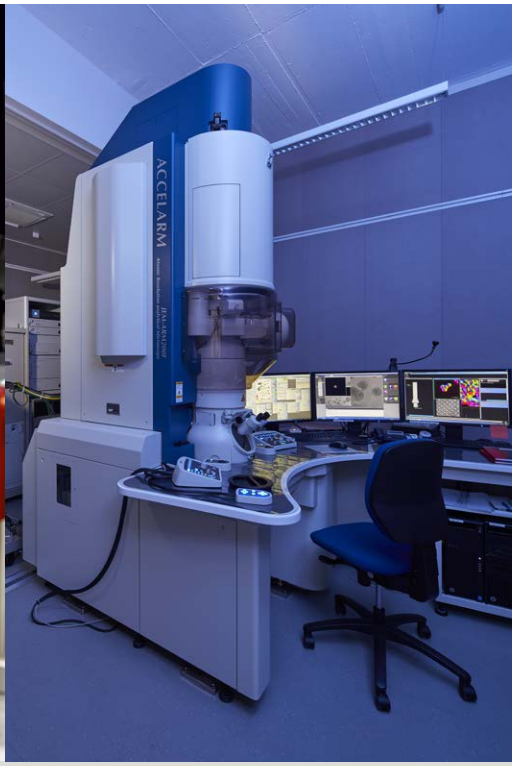
PADERBORN UNIVERSITY






# CeOPP

**Center for Optoelectronics and Photonics Paderborn**

Central Academic Facility of Paderborn University

## ... evolving Photonics for tomorrow's technologies

Broschure 2022

# Preface

The Center for Optoelectronics and Photonics Paderborn (CeOPP), founded in 2006, is an interdisciplinary scientific institution of Paderborn University. Embedded in the profile area of the same name, it not only bundles the technical expertise of the disciplines of physics, chemistry, electrical and communications engineering, but also offers a meeting space and inspiring framework for diverse collaborations and innovative research approaches.

The rapidly growing research field of photonics makes a significant contribution to meeting the challenges of our time in many different areas of life. The use of solar energy, the development of medical technology, the possibilities of optical communication, all the way to high-performance quantum computers - photonics plays a central role in all of these areas and thus represents an essential foundation for the digital transformation of our society.

Paderborn University has a proven expertise in this research field. The profile area “Optoelectronics and Photonics” and in particular CeOPP form the basis for many years of highly successful research, which has now gained a visibility that radiates far beyond the region. A significant factor in this is the decidedly interdisciplinary approach, which is becoming increasingly important in view of the complexity of current issues in many research areas. The promotion of interdisciplinary networking and cooperation is therefore an essential element of the research strategy at Paderborn University.

The impressive track record of CeOPP shows that this interdisciplinary approach is extraordinarily fruitful and produces forward-looking results. Just one example of the innovative research projects in the fields of photonics and quantum optics: is the collaborative research center SFB/TRR 142 “Tailored nonlinear photonics: From fundamental concepts to functional structures”, which has been working successfully for eight years now and is carried out in cooperation with the TU Dortmund University.

This brochure will give you an idea of the fascinating and multifaceted research projects of CeOPP and the scientists who are driving them forward with great commitment and at the highest scientific level. I wish you a stimulating read!

Prof. Dr. Birgitt Riegraf
President of Paderborn University
January 2022

# Table of Contents

# About CeOPP

Since 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, following 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 based on initially ten designated research groups. In the same year, a new research 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 in the fields of optoelectronics and photonics. 2008 marked 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 colleges from the TU Dortmund University.


In 2021, this program was successfully extended into a third funding period and will provide substantial support for the CeOPP members until 2025. 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 worldwide.

For teaching and education, the interdisciplinary structure of the CeOPP offers unique opportunities for Bachelor-, Master-, and PhD-students to acquire 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 contribute to the education and training of the next generation researchers in this field.

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, 21 designated members from the Paderborn University and five associated members joined the CeOPP. Together they cover important areas of the innovative optical technologies of today, as presented to you in this brochure.

Prof. Dr. Thomas Zentgraf, Chairman of CeOPP
Januar 2022

# CeOPP Board Members








## Professors

Prof. Dr. Donat As
Prof. Dr. Tim Bartley
Prof. Dr. Jens Förstner
Prof. Dr.-Ing. U. Hilleringmann
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Prof. Dr. Heinz-S. Kitzerow
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J.-Prof. Dr. Polina Sharapova
Prof. Dr. Christine Silberhorn
Prof. Dr. Andreas Thiede
Prof. Dr. Thomas Zentgraf
Prof. Dr. Artur Zrenner

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Dr. Manfred Hammer

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## Student Representative

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

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UNIVERSITÄT PADERBORN
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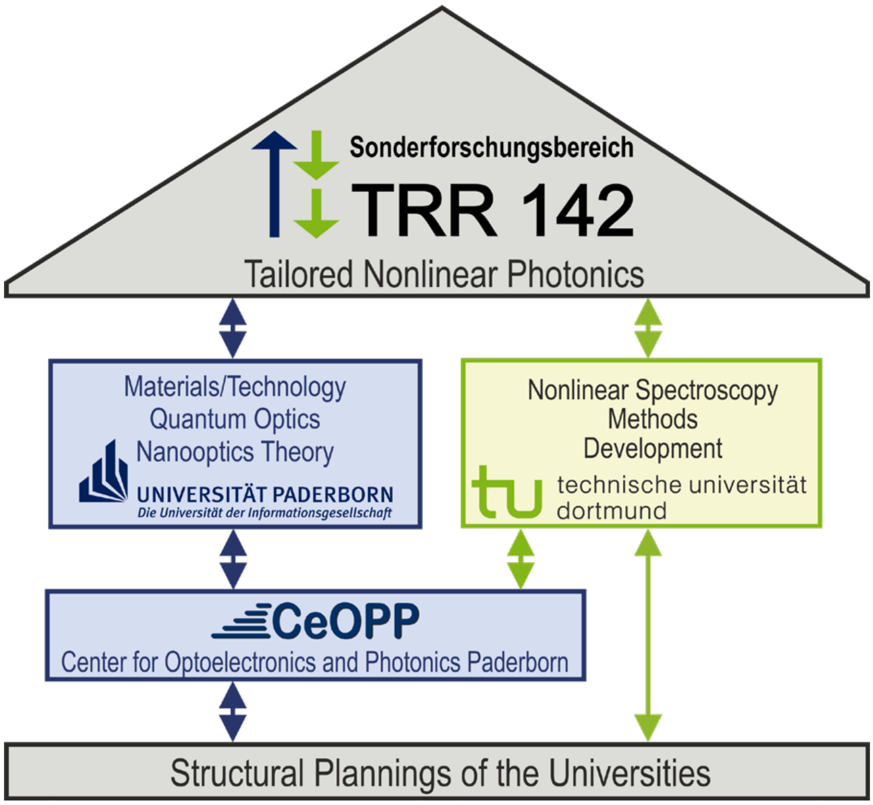
SFB TRR 142
technische universität dortmund

*Principal investigators of the SFB/TRR142*

Since 2014 the Collaborative Research Center/Transregio 142 funded by the German Science Foundation (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 Paderborn University and Technical University of Dortmund it combines the core expertise of Paderborn University in photonic materials, technology, quantum optics, and theory with the competence of the TU Dortmund in nonlinear spectroscopy.
For the participating researchers of the CRC/TRR 142, the CeOPP provides the full support throught the access of the cleanroom infrastructure and state-of-the-art lab space, which can be also accessed by the associated members of the CeOPP from TU Dortmund.

## 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:** **Light-Matter Interaction**
**B:** **Materials and Technology**
**C:** **Quantum Applications**

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.

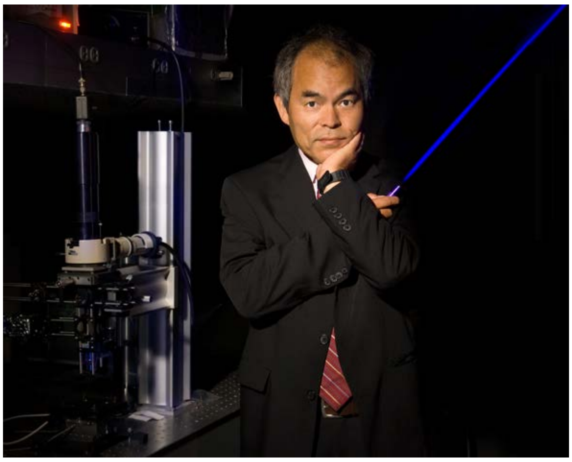
Further information: **http://trr142.uni-paderborn.de**

# 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.



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

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.

*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 established a new Priority Program “Electronic-Photonic Integrated Systems for Ultrafast Signal Processing“ (SPP 2111) which started in 2018.

The initiative is 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.

# Group III-Nitrides for Optoelectronics
## Prof. Dr. Donat As

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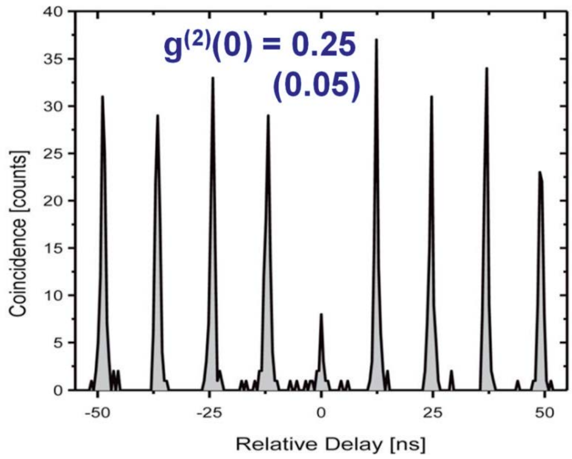
Group III-Nitride forms a new class of semiconductors for modern applications in opto-electronics and electronics. They form the basis for the well-known white light emitting diodes (LEDs) for energy saving future lightings and offer the way to fabricate blue and UV-lasers for gas spectroscopy or water 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.

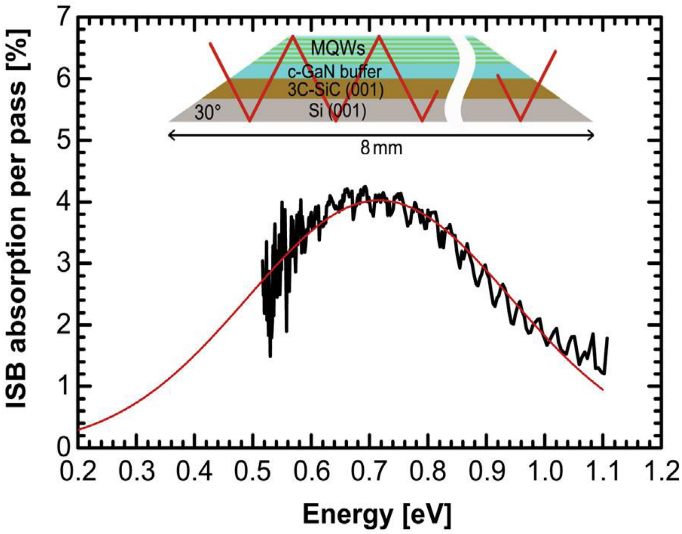



*Autocorrelation histogram of a single c-GaN QD emitting at 3.687 eV at 4 K. The excitation power was 20 mW and the PL decay time is about 360 ps. The number in the bracket is the background corrected value of $g^{(2)}(0)$.*

## Optoelectronic applications – Intersubband transitions

Low dimensional semiconductor structures allow the design of optical properties in solids and the study of ultrafast optical nonlinearities and quantum coherence. Especially optical inter-subband transitions (ISBT) in quantum wells and quantum dots are of great interest, since by proper tailoring of the material composition and well width the transition dipole-moments are severely strengthen and the absorption and the optical nonlinearities may become measurably enhanced.

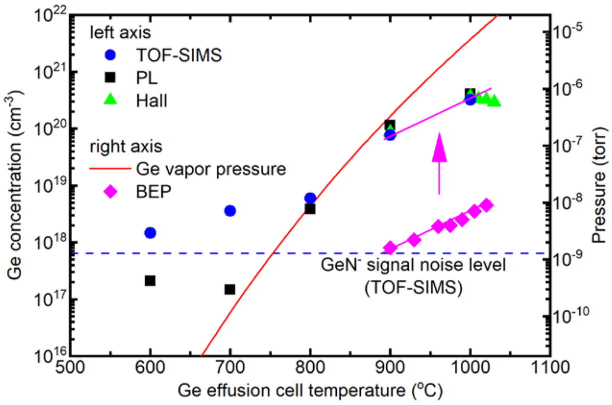
Due to the large band gaps and band discontinuities of the group III-nitrides AlN and GaN ISBTs in the wavelength range between 1.3 – 1.55 µm can be reached, which are important for telecommunication. Therefore, nitride based heterostructures have the potential to become a platform for all-optical switches and wavelength converters in the important near infrared spectral range. For the adjustment of the intersubband wavelength the determination of the well width, the roughness of the interfaces and the composition of the barrier material is absolutely necessary. The intersubband transition energy is measured via IR absorption. The Figure shows an IR absorption spectrum of such a cubic AlN/GAN MQW structure, demonstrating the successful fabrication of such a heterostructure.



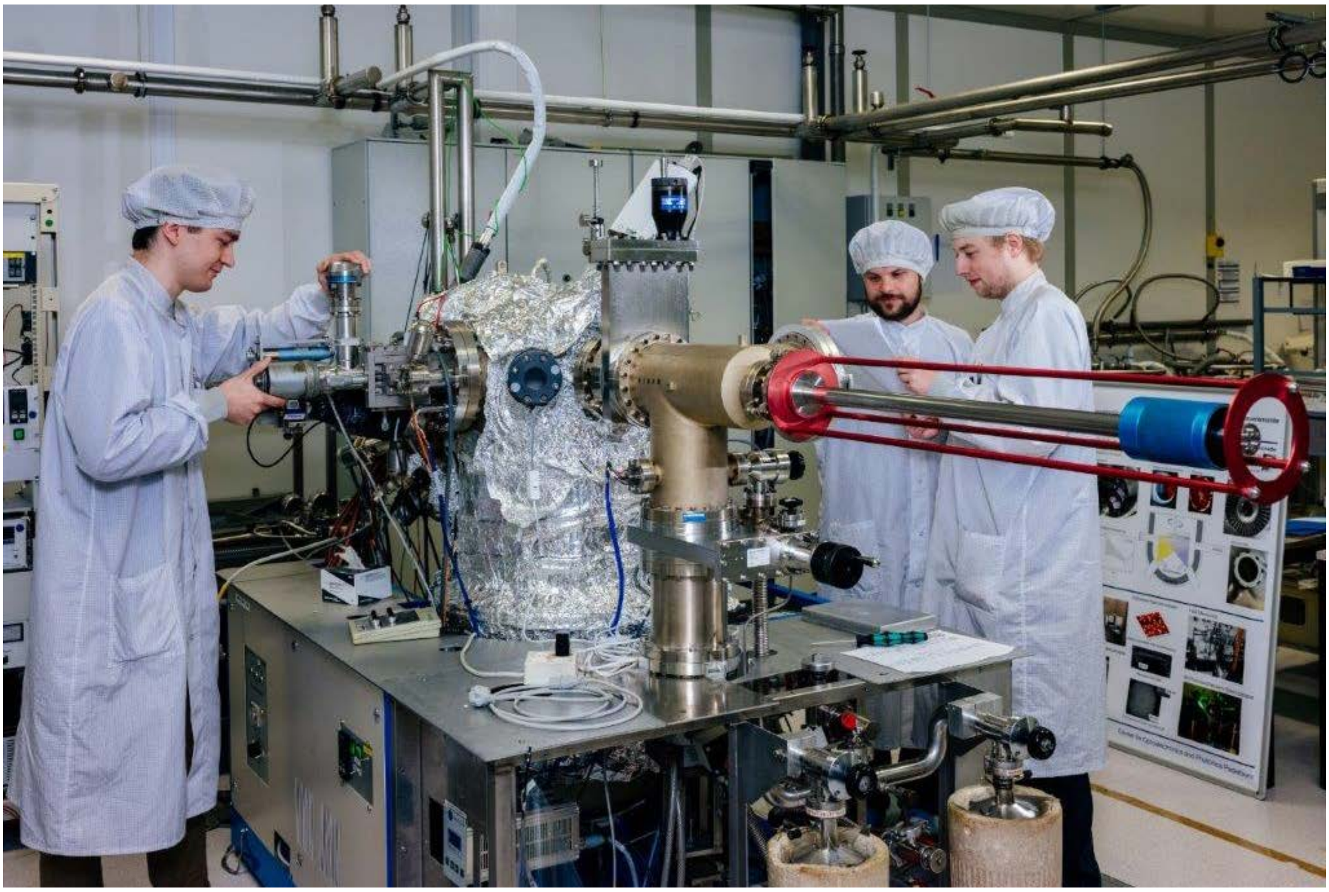

*Room temperature IR absorption spectrum at 0.7 eV (1,55 µm) of a cubic GaN/AlN Multi Quantum Well (MQW) structure. The red line is only a guide for the eye. In the inset the sample geometry is shown (UPB, Donat J. As).*

## Electronic properties - Ge doping of cubic GaN and $Al_xGa_{1-x}N$

The overarching goal to improve the performance the intersubband transitions in GaN/Al(Ga)N heterostructures has been to enlarge and utilize the resonant nonlinearity associated with. One central aspect is to achieve stronger n-doping of GaN/AlN heterostructures, in particular by using Ge. Ge is well suited for n type doping of cubic GaN and c-$Al_xGa_{1-x}N$. The maximum achieved donor concentration is 1.4 × $10^{20}$ $cm^{-3}$. This donor concentration is sufficient to enhance intersubband transitions in cubic GaN/AlN heterostructures. The Ge donor concentrations obtained by different characterisation methods are summarized in the Figure. From time of flight secondary ion mass spectroscopy (TOF-SIMS) depth profiles Ge concentrations are determined. In these measurements the Ge concentration was calibrated by using Ge ion-implanted reference samples. PL spectroscopy allows to calculate the donor concentration from the blue shift of the (D0, A0) transition due to Coulomb interaction with increasing donor concentration. Conversely, the donor concentration can be calculated from the energy shift. Room temperature Hall effect measurements were performed to determine the free electron concentrations of the layers, which are equal to the respective donor concentrations in case all donors are ionized. This is assumed to be valid for the degenerately doped layers. In the medium doping range the measured donor concentrations are in good agreement with the trend of the vapour pressure curve (see Fig.). However, at higher doping levels there is a deviation towards lower donor concentrations observed by all of the measurement methods. The beam equivalent pressure (BEP) of the Ge effusion source was measured to examine the actual amount of Ge supplied during growth.




*N-type doping of cubic GaN with Ge. The incorporated Ge concentration is plotted as a function of the Ge effusion cell temperature (UPB, Donat J. As).*




### Equipment & Methods

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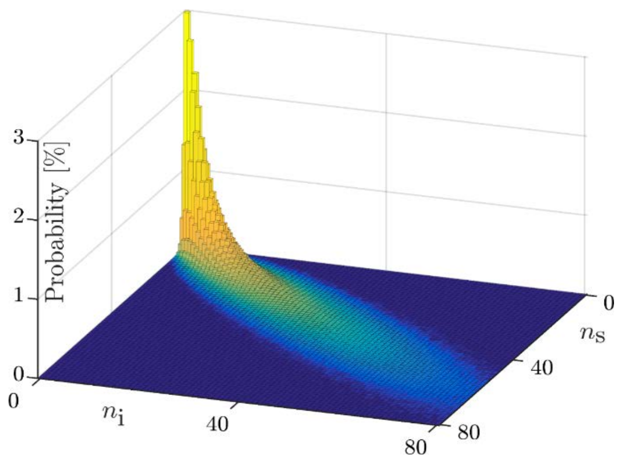
The Mesoscopic Quantum Optics (MQO) group uses light to expose nonclassical phenomena at large energy scales. Some of the most interesting and counter-intuitive consequences of quantum mechanics, for example superposition, wave-particle duality and nonlocality, are not part of our everyday experience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

We work closely with other research groups within Paderborn as well as the National Institute for Standards and Technology in Boulder, Colorado. Our approach combines sophisticated techniques in nonlinear optics, integrated optics and superconducting detectors in order to push the limits on building quantum systems, as well as theoretical techniques to deal with large data sets and develop protocols in the mesoscopic regime of quantum optics.

## Introduction

The MQO group investigates fundamental physics and develops quantum applications with mesoscopic-sized quantum states of light, all underpinned by enabling technology. 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 human 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. In this context, the research of the MQO group can be divided into three areas: developing enabling technology for mesoscopic quantum optics, fundamental physics with mesoscopic quantum states, and applications of mesoscopic quantum optics.

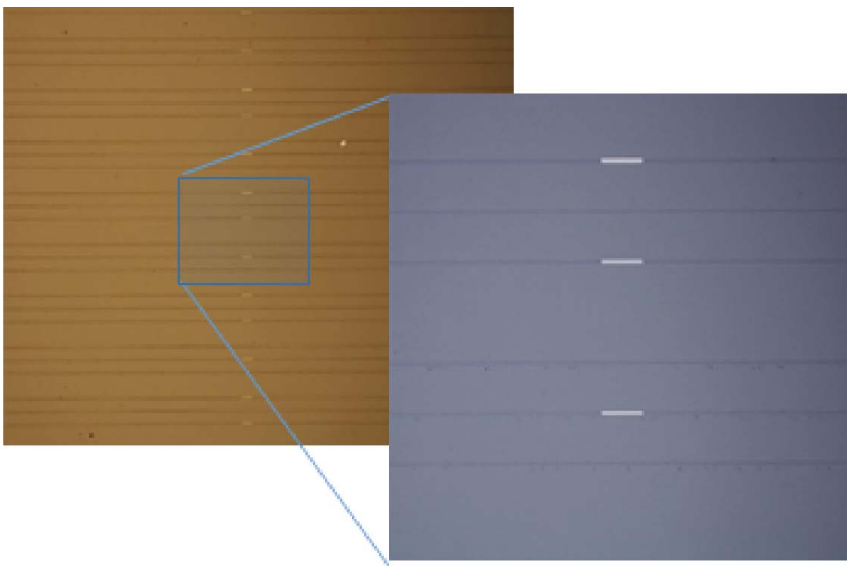



*Joint photon number distribution arising from strongly-pumped parametric down conversion in ppKTP waveguide. (UPB, Tim Bartley)*

## 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 techniques in 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 which go beyond what has been achieved 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").

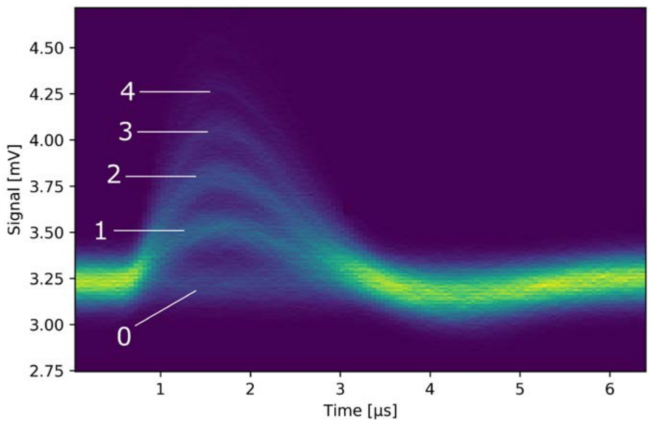
Not only are these interesting in the quantum domain, but understanding how lithium niobate behaves at these cold temperatures is also of fundamental interest. We are developing tools and techniques to characterise nonlinear interactions at cryogenic temperatures, and using these tools to develop models of the optical properties of nonlinear waveguides under this conditions.



*Deposition of thin-film tungsten on lithium niobate waveguides. (UPB Jan Philipp Höpker)*

## Fundamentals

The role of quantum mechanics in large systems raises some very interesting questions. Can local realism be violated using large numbers of photons? Can particle-like behaviour be seen in optical states containing 1000s of photons (analogous to wave-like behaviour of large molecules)? 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.

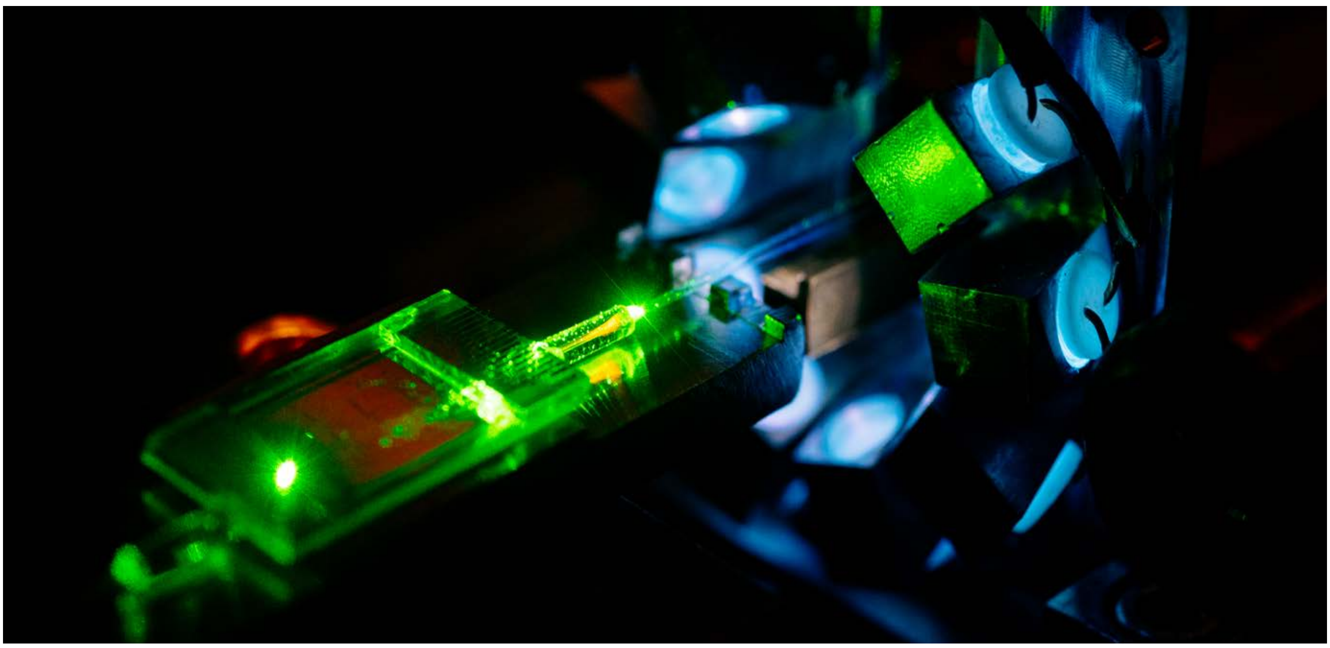



*Typical traces from a transition edge sensor of a coherent state. (UPB, Jan Philipp Höpker)*

We have been able to push the boundaries of these questions with engineered parametric down-conversion in periodically-poled KTP waveguids 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 of a large size, which can themselves be used to investigate quantum optics at large scales.



## Equipment & Methods

- Superconducting nanowire single-photon detectors
- 0.8K closed-cycle cryostats
- Free-space coupled 4K cryostat
- Laser lithography
- Electrical probe station
- Waveguide linear characterisation
- Single-photon scanning spectrometer
- Ultrafast laser systems
- Picosecond time taggers

# Theoretical Electrical Engineering
## Prof. Dr. Jens Förstner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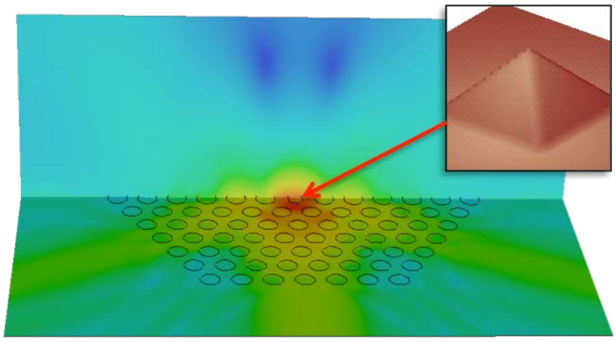
Since June 2013 Prof. Dr. Jens Förstner is head of the Theoretical Electrical Engineering group in Paderborn and new member of the CeOPP.
The group's research field covers a broad topical range from the simulation of light field propagation in photonic and plasmonic nanostructures to the microscopic 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*

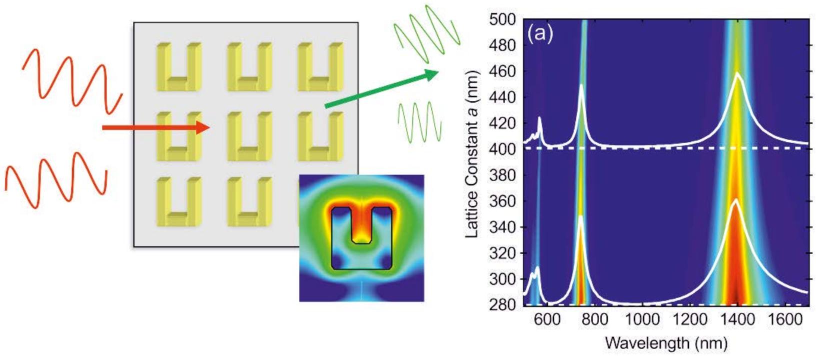
In metallic materials the high density of free electrons provides a plasma that can be optically excited. This leads to strong field enhancement and localization below the diffraction limit, i.e. below the vacuum wavelength scale. In plasmonic nanostructures this can be used to focus and steer light 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.

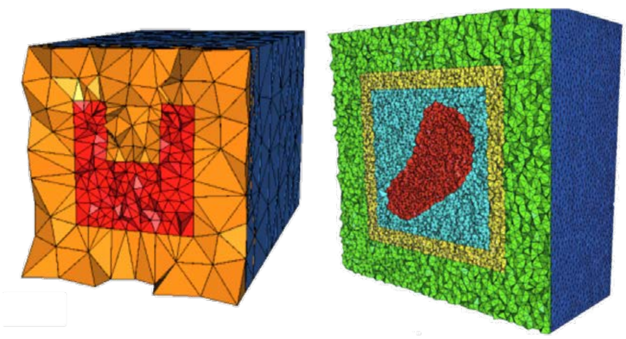
## Nonlinear, active, and chiral metamaterials

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.

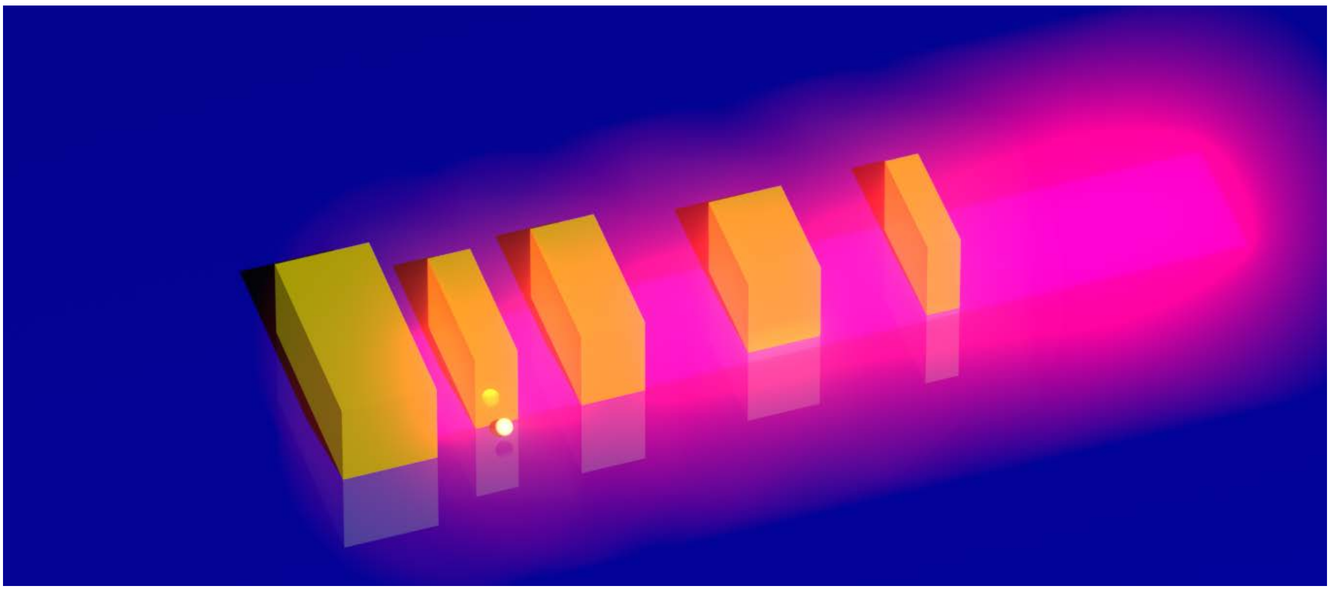


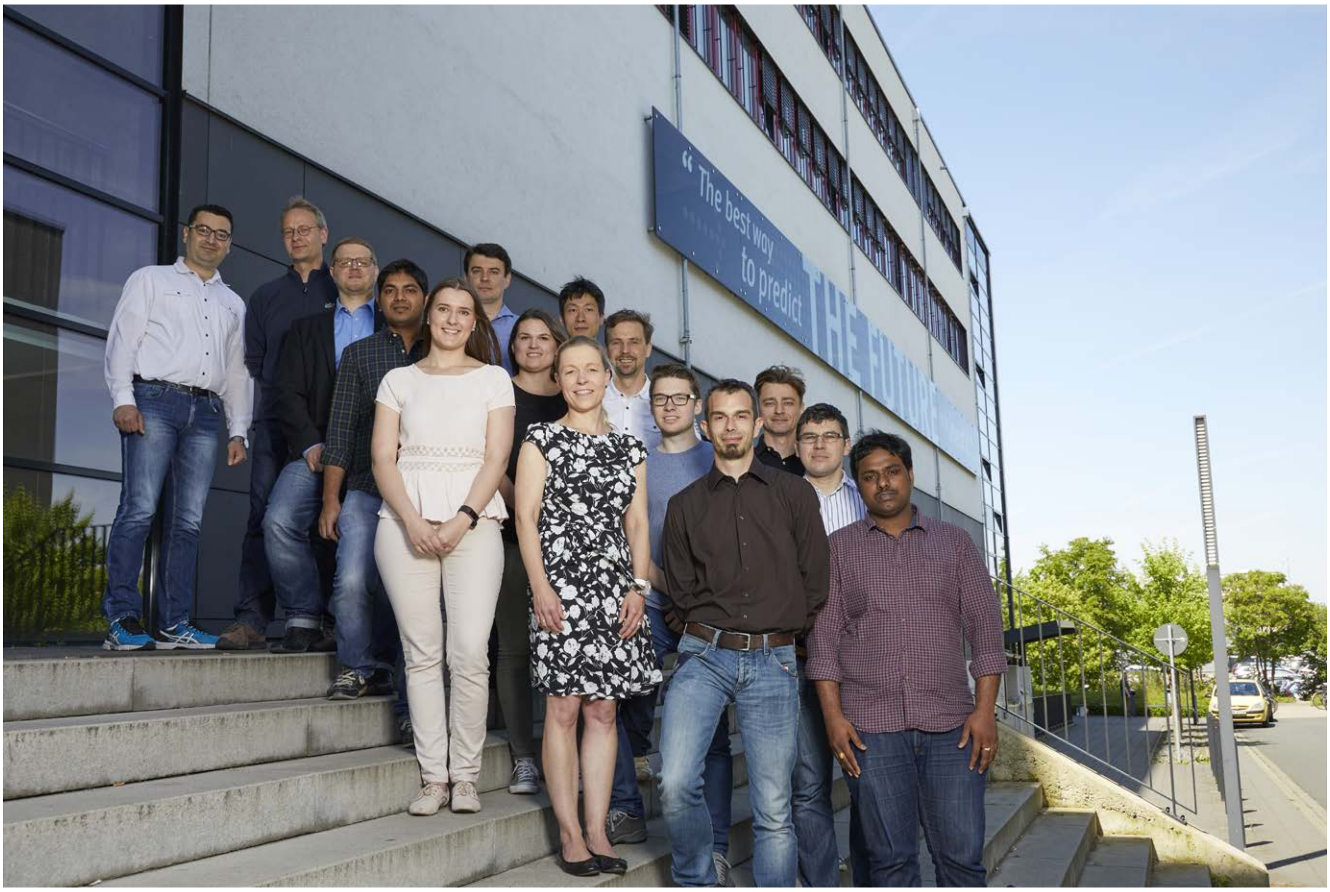

*Second Harmonic Generation of an array of split-ring resonator nanoparticles*



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

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).






### Equipment & 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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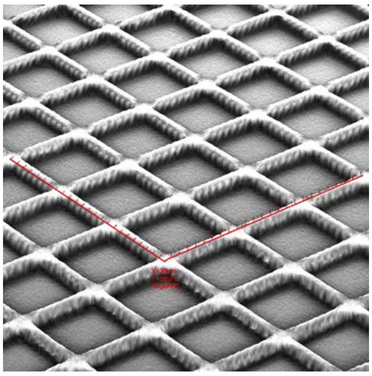
The research of the Sensor Technology group, funded in 1999, focuses on micro- and nanometer scale integrated circuits and sensors applying modern semiconductor processing.
In the area of automation technology new sensors or process applications are developed, e.g. passive RFID tags and readers with 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.

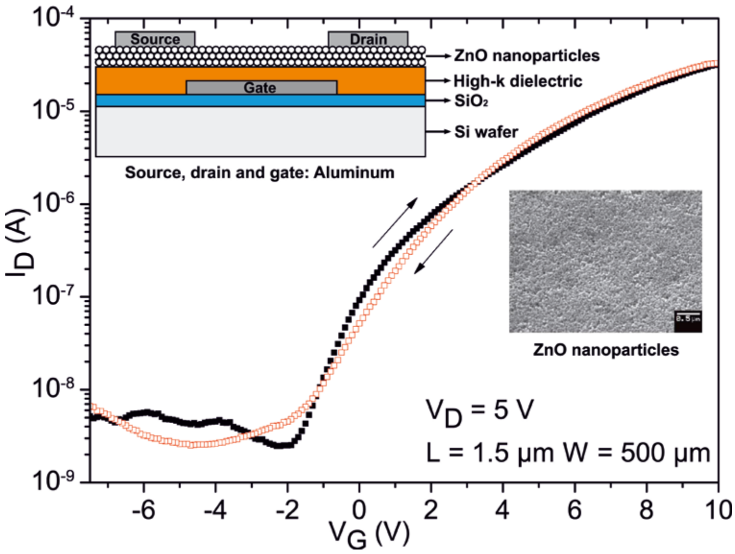
## Flexible Electronics

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.

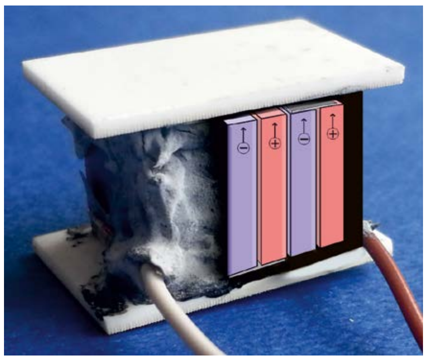



*Nanoparticle field effect transistor with associated input characteristics.*

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

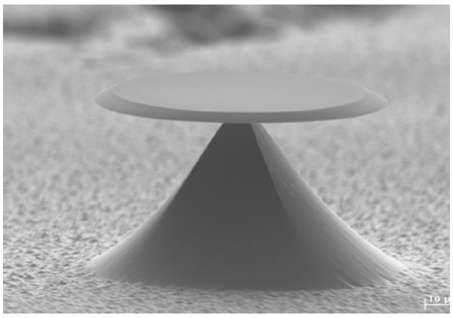
Fossil energy carriers become more and more expensive. Due to thermal losses a large amount of the energy is wasted to the ambient environment. With thermoelectric generators (TEG) some energy can be recovered using the material dependent Seebeck effect. Currently available TEGs are limited to about 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.



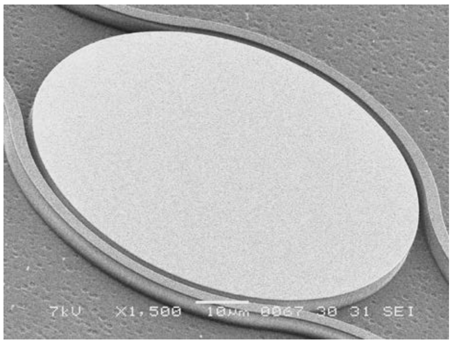
*Thermoelectric generator with titan silicide contacts.*

## 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*


## Equipment & Methods

- 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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Our research activities shall unravel mechanisms of intramolecular and supramolecular structure formation in nature and in synthetic systems. Final objective is the development of tools to control these processes. Time-resolved static light scattering (TR-SLS) and dynamic light scattering (TR-DLS), small angle neutron scattering (SANS) and small angle X-ray scattering (SAXS) are predominantly used to gain insight into the mechanisms of these structural transformations.

Four related topics can be distinguished:
1. Nucleation and growth of nanoparticles
2. Self-assembly of dyestuffs and proteins
3. Impact of macromolecular crowding on chain compaction and self-assembly
4. Polylactides as biobased materials for optical applications

## Nucleation and growth of nanoparticles

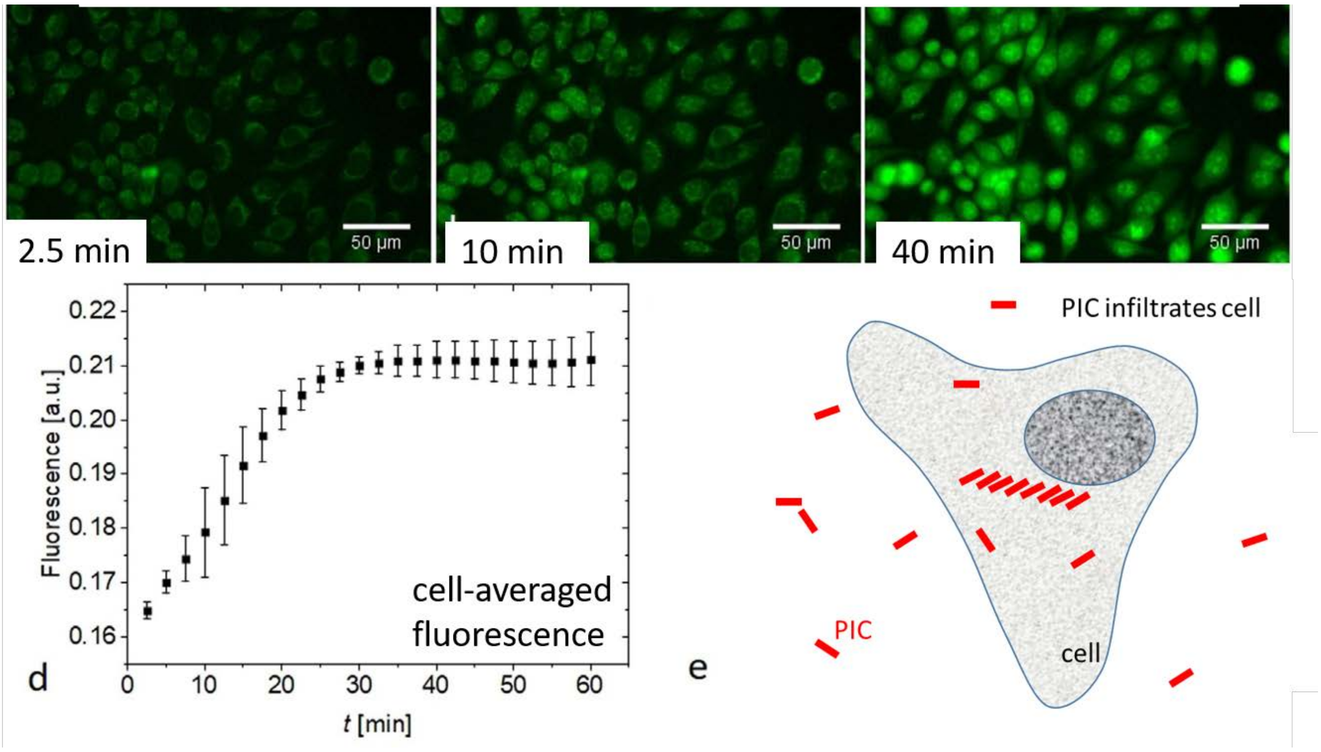
Nucleation and growth of particles are essential features of the formation of stable and metastable solid phases in nature and industry and are relevant to any bottom-up approach. Typical examples are the formation of carbonates, phosphates and silicates from supersaturated solutions relevant to biomineralization and scale formation in pipes, the generation of high performance nanoparticles of noble metals or of metal organic frameworks (MOF). We are currently working on the growth of eumelanin based biological pigments as an example from nature. Our goal is to unravel the formation mechanism of eumelanin pigments from the molecular build-up of precursors up to particles several 100 nm large. Growth and formation processes are predominantly analysed with time-resolved light scattering and SAXS. New kinetic models are developed and applied for the analysis of time-resolved scattering data in order to reveal nucleation and growth mechanisms for the formation of nanoparticles.

## Self-assembly of low molecular weight gelators and biopolymers

Numerous synthetic molecules like organic azo-dyestuffs form fiber-like aggregates in aqueous solution as various proteins do in living systems. The underlying processes are comparable to a polymerisation, leading to a structural diversity, just as complex as in macromolecular chemistry. The most recent example analysed in detail with time-resolved light scattering is the self-assembly of the cationic dyestuff pseudo-isocynanine chloride (PIC). Experiments on biological systems included the behaviour of vimentin, an intermediary filament protein from the cytoskeleton, and of fibrinogen involved in blood clotting. It is the final goal to unravel mechanisms of self-assembling in order to control such processes and to develop synthetic systems in analogy to hierarchical structure formation in nature.

## Impact of macromolecular crowding on chain compaction and self-assembly

Enzyme catalysed metabolism, conformational changes of proteins or DNA as well as the formation of hierarchical structures with proteins are common processes in living cells. Their investigation in vitro is typically based on experimental conditions at properly adjusted pH, salinity, temperature and concentrations of the components directly involved in the respective processes. Although helpful already, such investigations neglect the crowded environment in cells, generated by the presence of osmolytes, chaperones and the many other biopolymers. We develop synthetic model systems which mimic biological environments and at the same time reveal distinct aspects of morphological transformations under such crowded environment. One example is the aggregation of the cationic dyestuff pseudo-isocynanine chloride (PIC) in the absence and presence of various model crowders like Ficoll or poly(ethylene glycol). The choice of PIC is based on two features: its aggregation bears a striking analogy to the self-assembly of many proteins and its aggregated state provides a characteristic fluorescence pattern highly useful for in-cellulo experiments.




*Exemplary fluorescence images of PIC aggregation in HeLa cells at 21 °C, a) 2.5 min, b) 10 min, c) 40 min after addition of PIC (scale bar 50 mm), d) aggregation kinetics of PIC measured by the cell-averaged fluorescence intensities based on three independent measurements, e) Model for PIC aggregation inside cells. (Hämisch et al. Chem. Eur. J. (2020) 26 (31), 7041-7050)*

## Polylactides as biobased materials for optical applications

Biobased polylactides are potential candidates for optical applications like lenses, reflectors or light guides, where it is supposed to replace poly(methyl methacrylate) and polycarbonate. In collaboration with groups from other universities, the impact of additives to or irradiation of polylactide materials on the crystallization behavior and on the envisioned optical applications is investigated. Our group contributes with two topics: (i) Polylactides and colloidal or polymeric additives will be characterized by means of light scattering or Fraunhofer diffraction in order to make available structure-property relationships relevant for an application of the analysed samples in materials. (ii) The melting and crystallization pattern of the polylactide-based materials developed by collaborating groups is investigated in detail by means of a home-built small-angle light scattering (SALS) device. SALS makes accessible a time-resolved recording of the evolution or melting of crystals, which are crucial to the optical properties of the respective materials.

## Equipment & Methods

- 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
- Home built small angle light scattering instrument
- Differential refractometers

# Hybrid Quantum Photonic Devices
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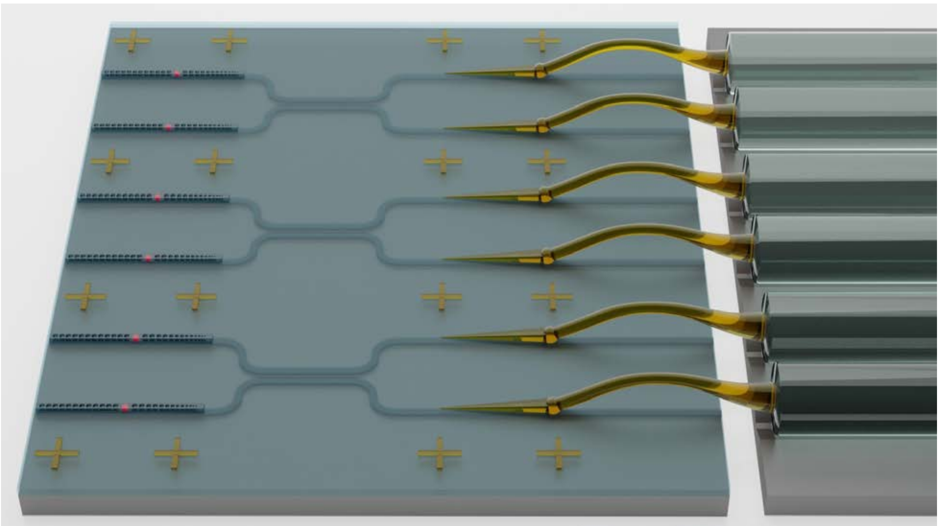
Our Hybrid Quantum Photonic Devices (hqpd) group develops novel devices for photonic quantum technologies, with a particular focus on quantum communication and quantum computation applications. Our research focuses on the investigation of nanometer-sized quantum light sources based on semiconductor and 2D materials, nanofabrication of photonic integrated circuits, the development of quantum memories as well as cryogenic electronics, and the integration and coupling of the individual devices with each other.

In particular, the miniaturization of individual devices and their integration on photonic circuits plays a critical role in the everyday viability of photonic quantum technologies. Unfortunately, different devices are often not directly compatible with each other and therefore cannot be monolithically integrated on a single chip. In our group, we aim to develop novel hybrid or heterogeneous integration methods to combine different components on a circuit without sacrificing performance of the individual components.

The hybrid quantum photonic devices (hqpd) laboratory focuses its research on the realization of building blocks for photonic quantum technologies. One of the central components for our hybrid photonic circuits are single photon sources, such as semiconductor quantum dots or 2-dimensional materials. These emitters will be embedded in resonator structures and transferred on photonic integrated circuits. Quantum dots are currently the purest single photon light source. Furthermore, these emitters can emit entangled photon pairs on demand, a key component for future quantum repeaters which are urgently needed for the realization of quantum networks. Our research rests on three pillars: i) cryogenic quantum optics experiments to harvest the quantum properties of our emitters and our circuits, ii) nanofabrication of photonic integrated circuits as on-chip platforms for photonic quantum technologies, and iii) cryogenic electronics for ultra-fast electrical control of our quantum systems.

## Quantum optics experiments

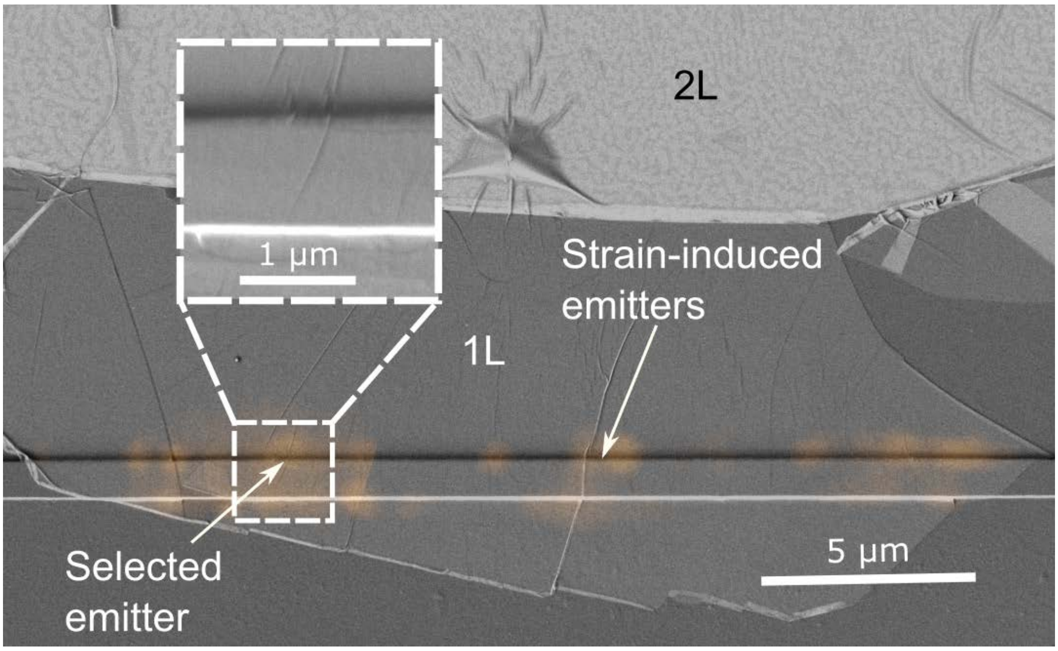
To perform our quantum optics experiments we use different continues wave and pulsed laser sources to excite our quantum emitters which are cooled down to liquid helium temperatures in a cryogenic photonic probe station. This allows to perform cryogenic confocal microscopy to localize quantum emitters as shown in Fig3. We use superconducting single photon detectors to proof the quantum nature of the emitted light of our solid-state quantum light sources in complex correlation spectroscopy experiments. Most of our advanced measurement setups are home-made, such as transmission spectrometers, phase-stabilized Mach-Zehnder interferometers, and Fabry-Pérot interferometers to maintain at the cutting edge of quantum optic sciences.



*Hybrid integration of semiconductor quantum light sources on photonic integrated circuits.*

## Quantum photonic integrated circuit fabrication

Our group`s research heavily relies on nanofabrication, either in our own small fabrication facility in the A building or in the common cleanroom in the P8 building. A key factor in for these research activities are numerical optimization of our devices on our own workstation. based on our simulations we design the on-chip components such as waveguides, resonators and couplers. Using electron beam and laser lithography system we define our nanostructures, such as photonic integrated circuits and resonator coupled quantum light sources, and use different wet and dry-etching methods to fabricate our devices. A fully integrated circuit consisting of transfer printed photonic nanobeam cavity coupled quantum dots, waveguides, beamsplitters and photonic wire bonds to couple to single-mode fibers is schematically shown in Fig2. In our group we design, nanofabricate these chips and later characterize them in our quantum optics laboratory.




*Our custom-made transfer setup enables versatile integration of two-dimensional materials such as $WSe_2$ as on-chip single-photon sources in photonic integrated circuits. SEM picture of a SiN waveguide overlaid with a cryogenic photoluminescence map image of strain-induced quantum emitters in a monolayer (1L) of $WSe_2$.*

## Ultra-fast cryogenic electronics

Based on the long-lasting expertise at Paderborn University our group designs ultra-fast cryogenic electronic circuits as on-chip switches, coherent control, and read-out electronics. These circuits are first simulated and designed, and later integrated into our quantum optics experiments. Ultra-fast cryogenic electronics serve as a classical control building block of our quantum photonic integrated circuits. We focus on coherent optoelectronic control of quantum systems, ultra-sensitive photocurrent readout, as well as fast feed-forward operations. Two important applications of our electronics are the control of on-chip modulators as well as the read-out of superconducting single photon detectors. Together with logic operations these would be the main ingredients to realize feed-forward operations for measurement-based quantum computing.

## Equipment & Methods

- Cryogenic photonic probe station
- Superconducting single photon detector
- Dilution refrigerator
- Transfer setup
- Cryogenic spectroscopy
- orrelation spectroscopy
- Pick-and-place and transfer printing
- Nanofabrication including e-beam and dry-etching

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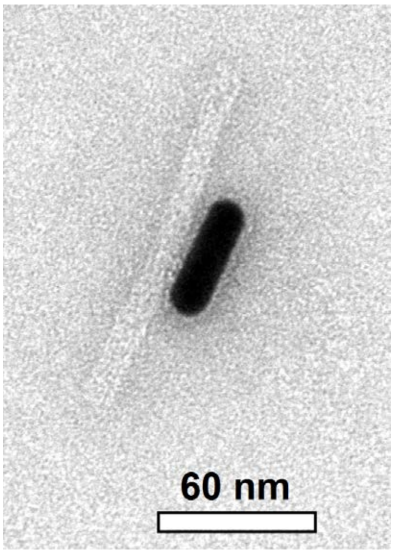
Liquid crystals are ordered fluids that play an important role in living organisms and in information technology. Flat TV and computer screens make use of thermotropic calamitic liquid crystals, which consist of rod-like molecules that are preferentially parallel aligned. This orientational order leads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

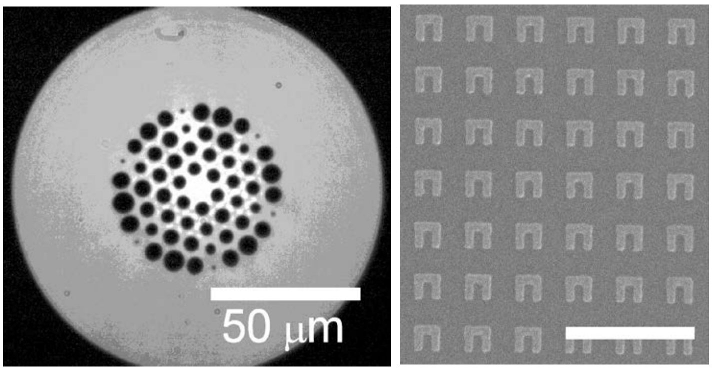



*Gold nanorod on a DNA origami nanostructure [TEM, recorded by Bingru Zhang]. Right: Cromoglycate needles induced by DNA nidi decorate a LC [polarisation-optical micrograph, scale bar: 200 µm].*

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.

## 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

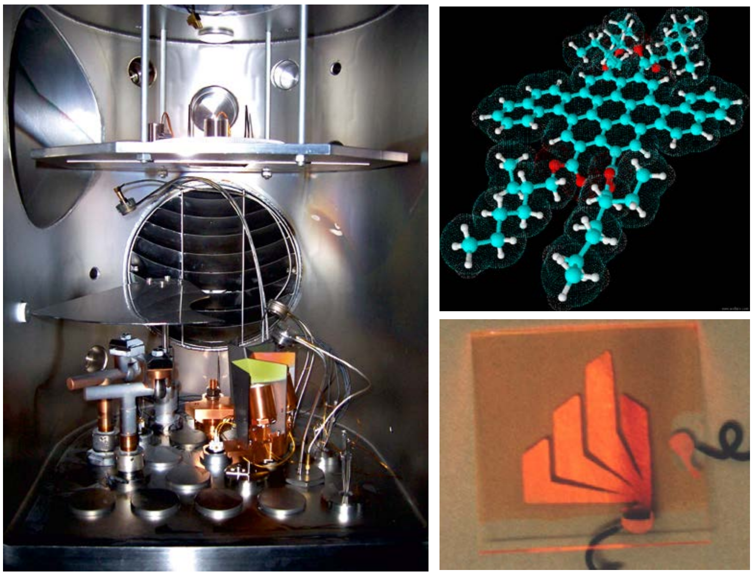



*Micro- and nanostructure, which were filled or covered with a liquid crystal. Left: photonic crystal fiber, right: array of plasmonic split ring resonators (right scale bar: 1 µm).*

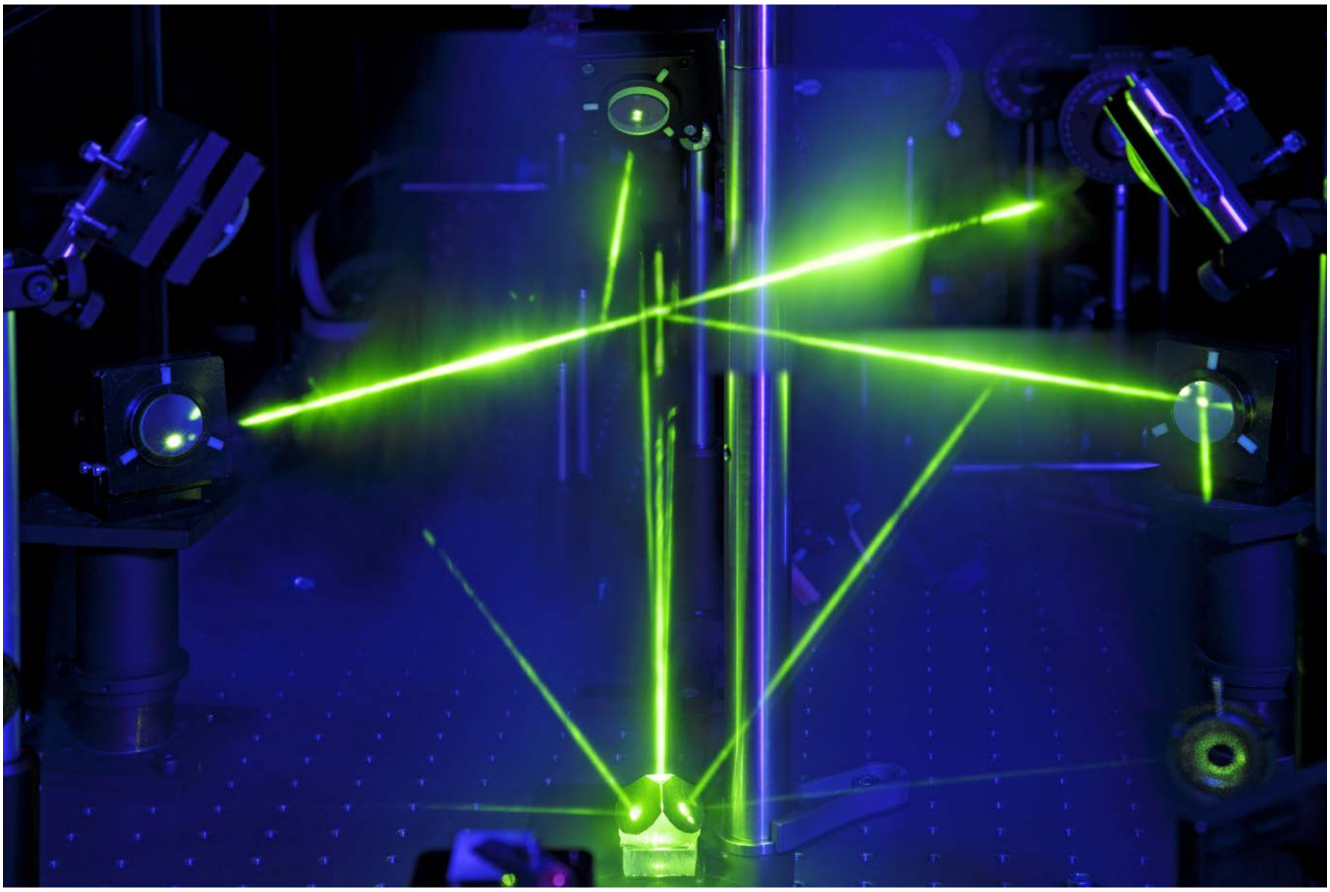
kind are embedded in a LC. Their transmission spectra can be controlled by thermal addressing, by applying voltages or by non-linear optical effects, such as the “colossal optical nonlinearity”, an extremely large optical Kerr effect.

## 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.*



## Equipment & Methods

- 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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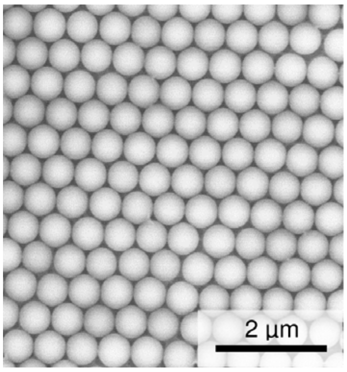
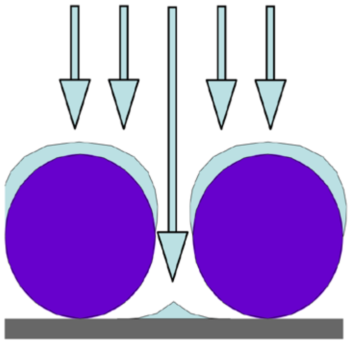
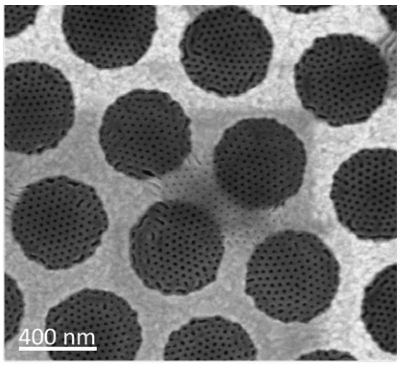
Modern materials design and technologies based on novel materials rely on the ability to tailor the morphology, inner structure and chemical composition of solids at the nanoscale. Nanostructures enable new materials applications in optics, electronics, computing, energy harvesting, chemistry, the bio-med sector and others. Depending on the purpose in mind, a broad range of different fabrication techniques is used to create nanomaterials.

We focus on bottom-up techniques, in which self-organization leads to the formation of regular nanoscale patterns, allowing for a low-cost fabrication of nanopatterns on large areas. In particular, nanosphere lithography and block-copolymer lithography are used to produce patterns in the 50-500 nm and the 10-50 nm range, respectively. In order to fully exploit the technological potential of such techniques, precise knowledge of the physical mechanisms influencing the interplay between materials fabrication conditions, resulting nanostructural properties and the macroscopic materials characterristics is required.

To achieve this, state-of-the-art (analytical) transmission electron microscopy is employed in our research group, allowing for materials characterization at the nanometer, atomic or even sub-atomic level. Emphasis is placed on materials which are hot candidates for future opto-electronic and photonic devices, including 2D photonic crystals, plasmonic nanostructures and heteroepitaxial semiconductor systems.






*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


*The new high-resolution (scanning) transmission electron microscope.*

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.

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

## Equipment & Methods

- 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
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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.

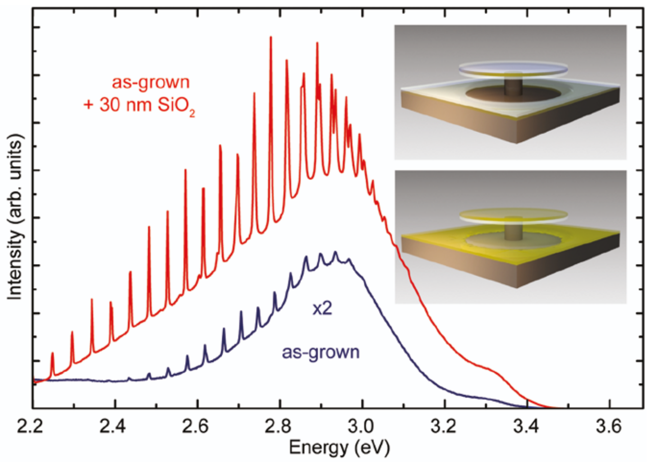
Another important goal of the research activities in the group is to develop photonic devices with all-optical control, which could become key building blocks in photonic integrated circuits. Here, hybrid devices made from semiconductors and molecular materials are investigated.

## Wide gap photonic devices

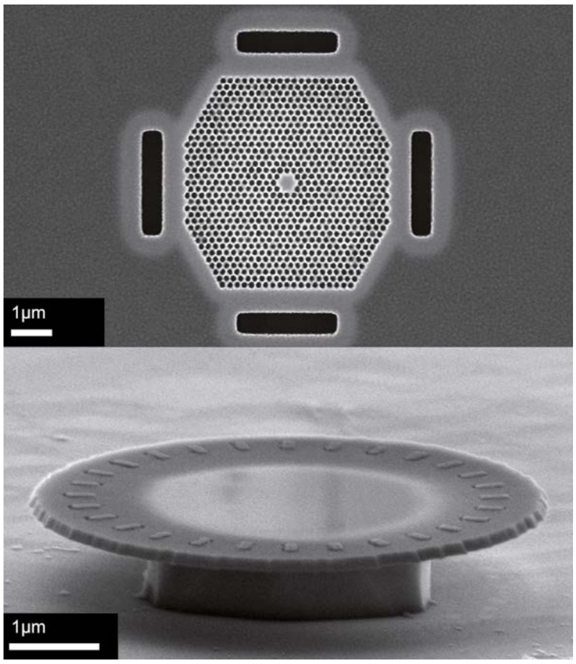
Zinc oxide (ZnO) is a very interesting material for photonic devices due to a number of unique features. Among those are the large band gap, covering the blue and UV spectral range, the large exciton binding energy (60 meV in bulk) and the lack of inversion symmetry, leading to strong and unusual nonlinear 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.




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

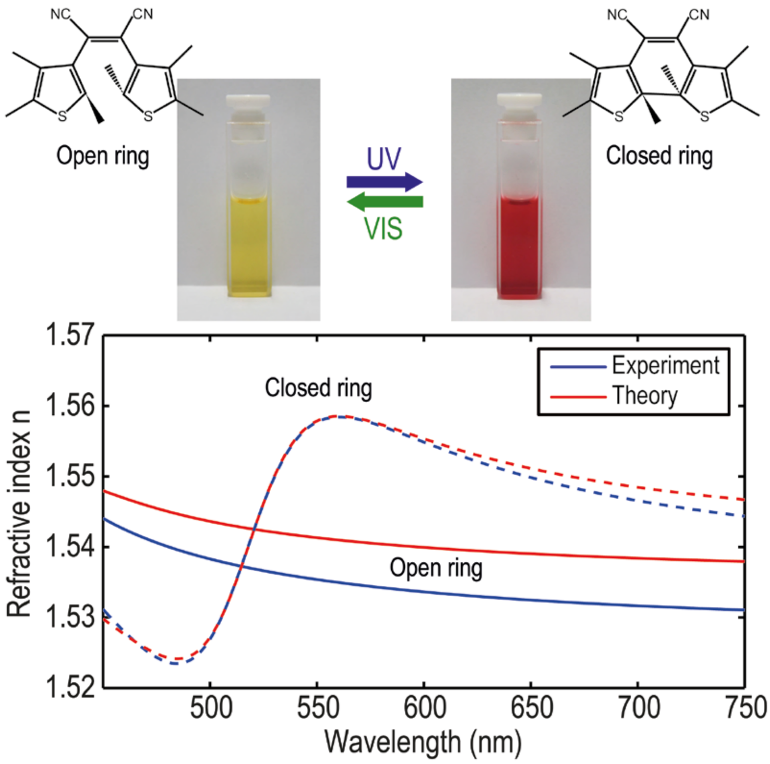



*Top: ZnO-based photonic crystal membrane. Bottom: $SiO_2$-based nanoplasmonic ring resonator with Ag dipole antennas.*

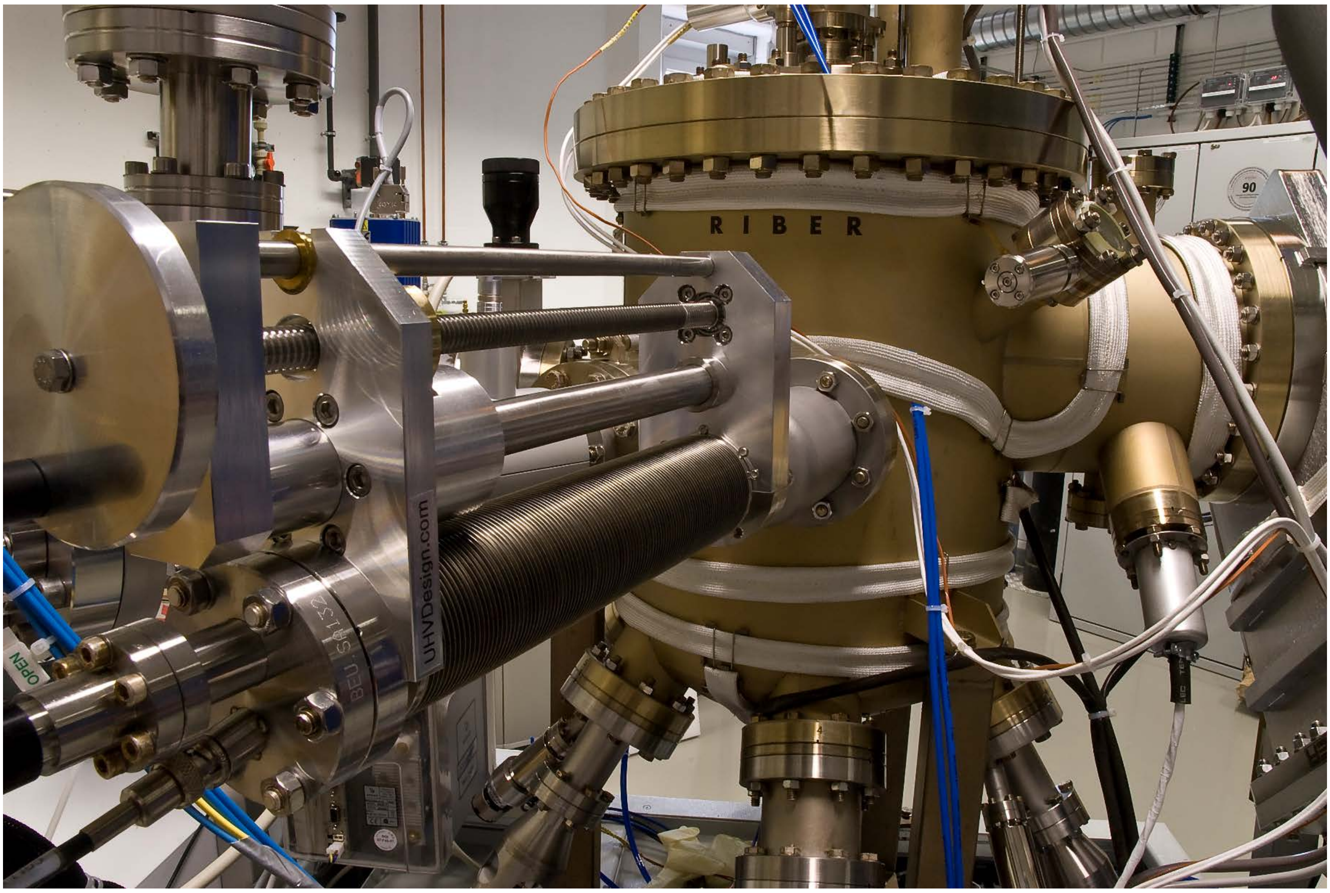
The strong polarity of ZnO, however, makes conventional wet etching techniques in this material system difficult. Therefore, the group has developed a number of different patterning techniques to tackle this problem and to achieve ZnO-based resonators with full photonic confinement in all three dimensions. 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.

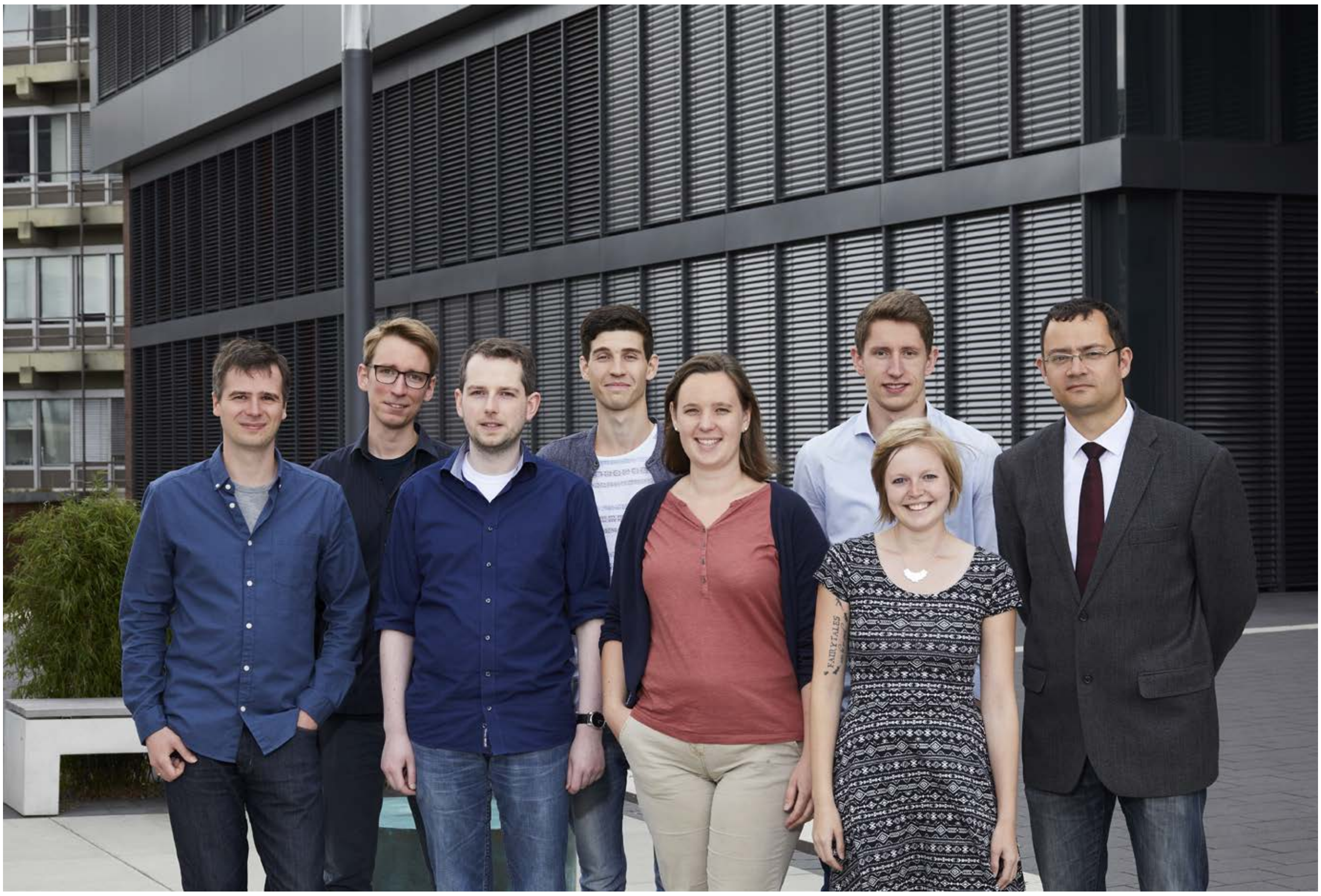
## Molecular driven photonic switches

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.*





## Equipment & Methods

- 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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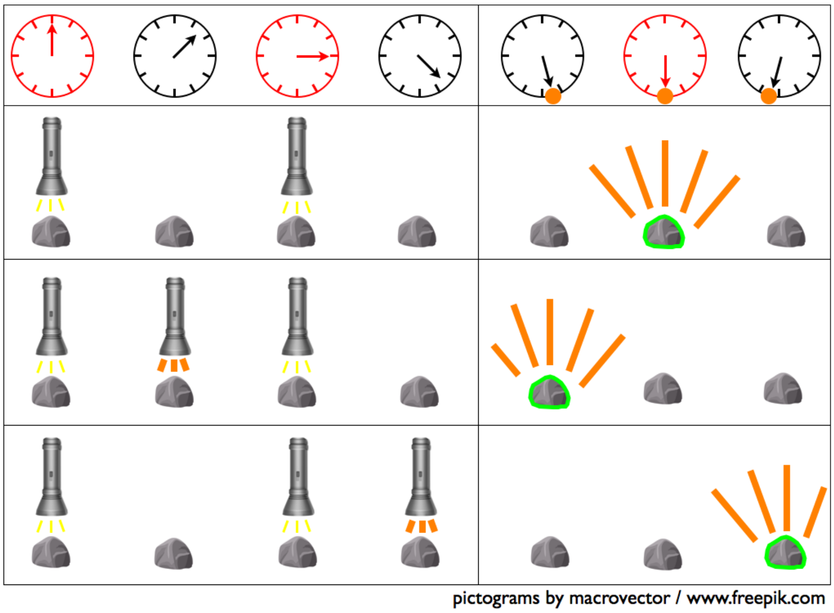
Nanostructures offer fascinating possibilities to modify both the electronic states and the light field. Suitably designed systems allow one to control the light-matter interaction and thus to achieve and utilize desired linear and nonlinear optical, quantum optical, and electronic properties.

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 and quantum 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.

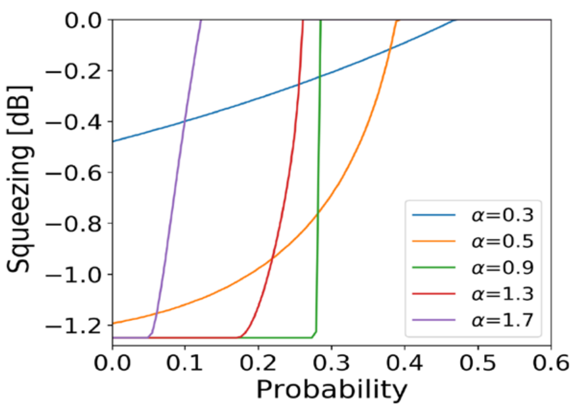
## Precise temporal control of photon echoes

The time-resolved four-wave-mixing signal of inhomogeneously broadened optical transitions is emitted as a so-called photon echo. This echo appears temporally delayed with respect to the last incident pulse and its delay is exactly given by the time difference between the first two exciting pulses. Recently it was shown theoretically and experimentally that by additional optical pulses it is possible to precisely control the emission time of photon echoes, i.e., to advance or retard them. This technique might be useful for nanophotonic circuits in which accurate temporal positioning of light pulses is required.




*Schematical illustration of the photon echo timing: Normal photon echo (upper row), advanced photon echo due to a pre-pulse (middle row), and retarded photon echo due to a post-pulse (lower row).*

## Generating two-mode squeezing with measurement-induced nonlinearity

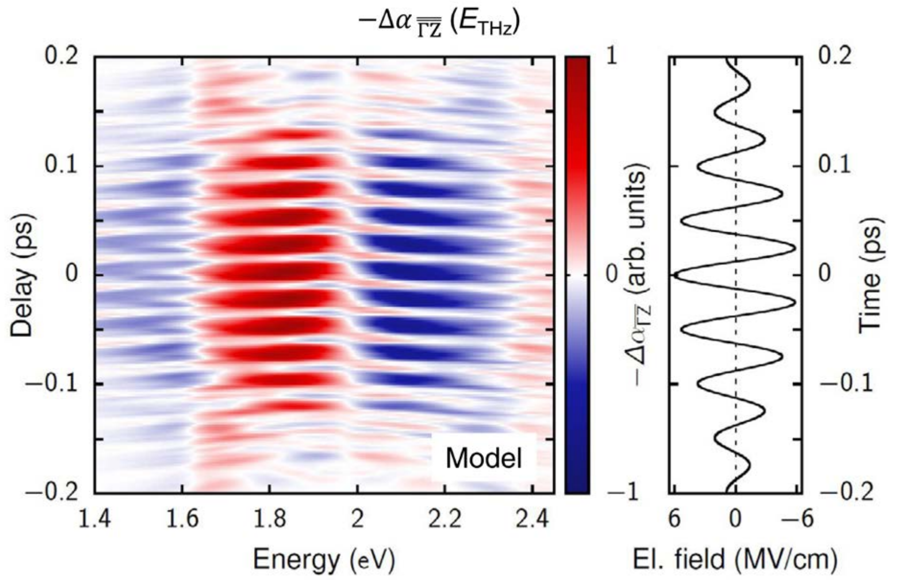



*Measurement-induced two-mode squeezing as function of the probability for different amplitudes of coherent input states.*

In a two-mode interferometer, measurements, i.e., the detection of photons, can induce nonclassical effects. For example, for certain parameters measurements within the interferometer lead to the generation of two-mode squeezing. The amount of achievable squeezing depends on the detection probability, the phase inside the interferometer, the choice of the input states, and the losses.

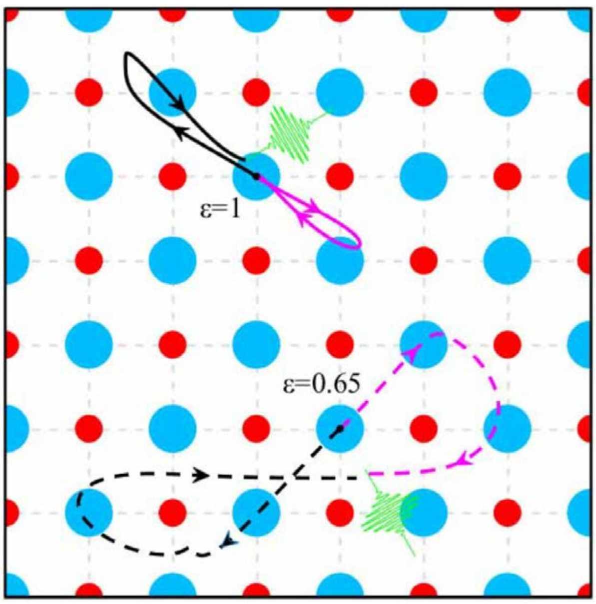
## Wannier-Stark localization in a polycrystalline perovskite

The optical properties of polycrystalline MAPbI3 can be modified drastically and on ultrafast time scales by intense pulses of Terahertz radiation. The large lattice periodicity and the narrow electronic energy bandwidth along a high-symmetry direction of the MAPbI3 crystal allows one to realize Wannier-Stark localization with relatively small field amplitudes. The possibility to reversibly and rapidly change the optical properties evidences the potential of this material for ultrafast light modulation and further photonic applications.




*Calculated negative absorption change as function of time and frequency for driving with an intense Terahertz pulse.*

## Collision dynamics in high harmonic generation




*Electron (black) and hole (magenta) trajectories for circular (solid lines) and elliptical polarization (dot-dashed lines).*

High harmonic generation (HHG) has great prospects for applications like short-wavelength light sources and is a versatile tool for imaging the internal light-induced dynamics in crystals with atomic scale spatial and attosecond temporal resolution. We reveal that the elastic scattering at neighboring atoms can dramatically influence the recombination of an electron with its left-behind hole. This process is demonstrated to be the fundamental reason for the anisotropy of the interband HHG that has been measured in bulk crystals. Our theoretical approach provides a unifying picture for several experimental observations and theoretical predictions.

## Equipment & Methods

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

# Optical Communication and High-Frequency Engineering

## Prof. Dr.-Ing. Reinhold Noé

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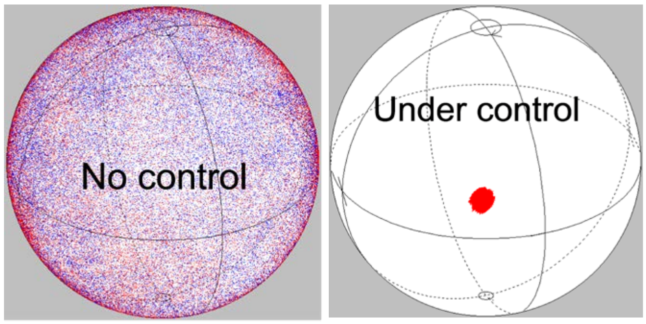
Optical communication transmits information for internet and telephone. At 1.55 µm wavelength the attenuation of the glass fibers is so small that after 100 km there is still 1/100 of the transmitted optical power available. The bandwidth is about 1/5 of the light frequency, roughly 40 THz. This is ~1000 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*

Deutschland
Land der Ideen
Ausgewählter Ort 2011

GERMANY
AT ITS
BEST
NORDRHEIN-WESTFALEN

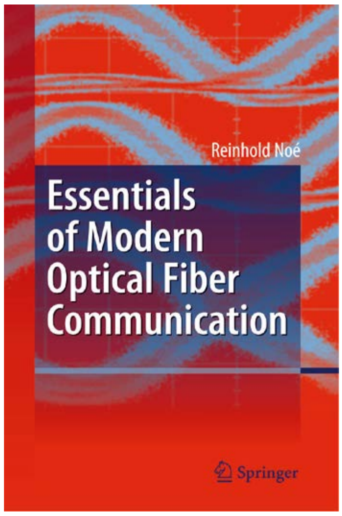
*Awards received for ultrafast optical polarization control*

### 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.

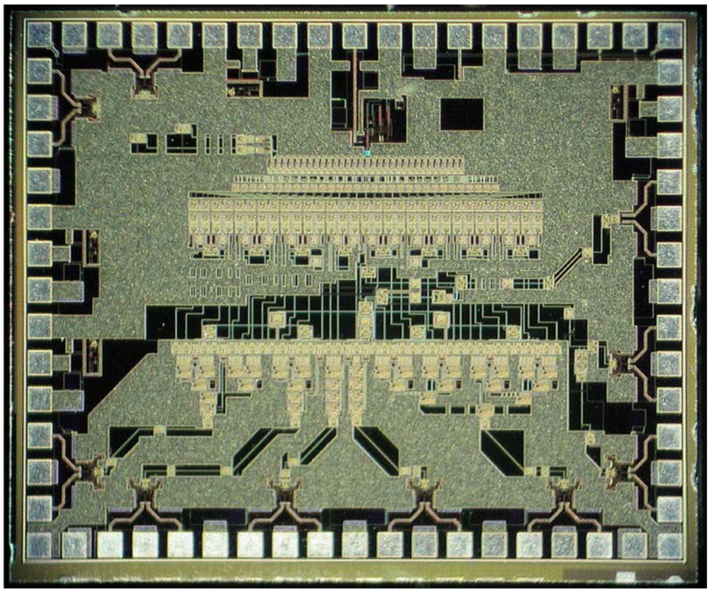
Furthermore, with fast polarization control, we have achieved a bitrate world record of 200 Gigabit/s over a 430 km distance for a single channel (2010). As of 2014, the used symbol rate 50 Gbaud is still a world record for realtime transmission with ≥4 bit/symbol.

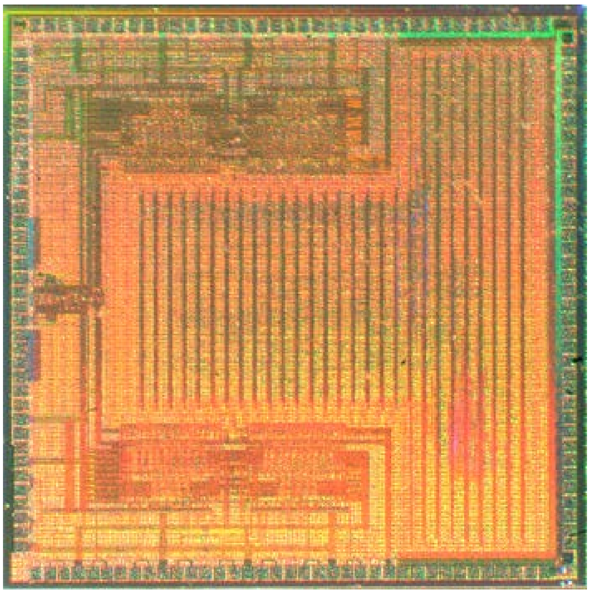
*The innovation prize 2008 of the Land Nordrhein-Westfalen in the category innovation was awarded to Reinhold Noé and Ulrich Rückert.*




*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.






## Equipment & Methods

- 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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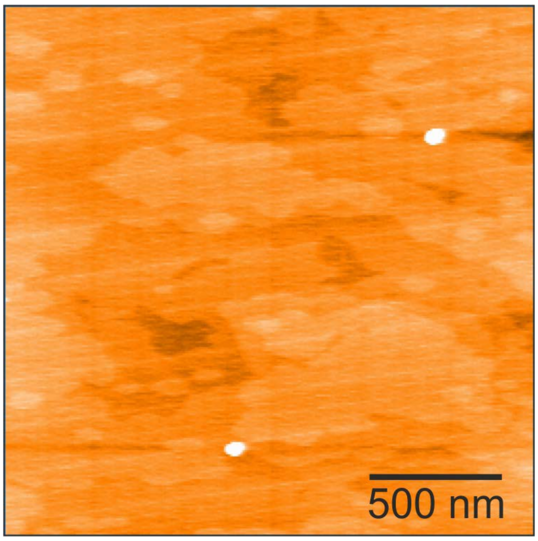
The group of Optoelectronic Materials and Devices at Paderborn University was established in 2012 and focuses its research on the fabrication and characterization of semiconductor heterostructures and heterostructure based devices. We employ molecular beam epitaxy, which allows the fabrication of heterostructures 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 heterostructures, functional structures as micro-resonators or devices as diodes are fabricated and characterized.

## Nanostructures based on group-III arsenides and antimonides

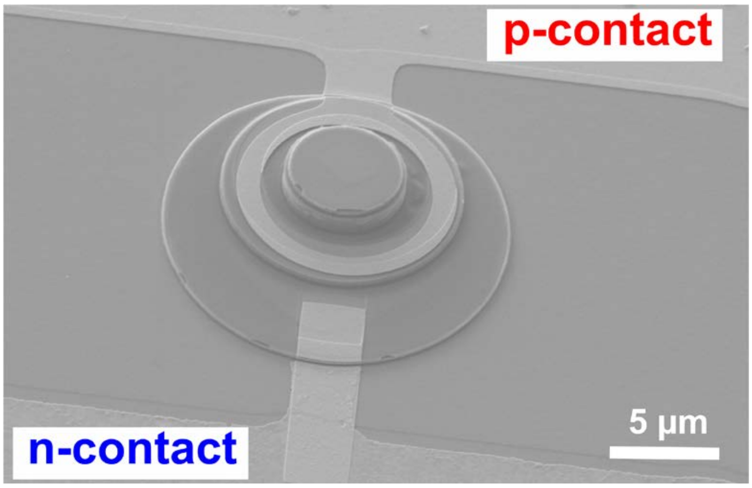
Group-III arsenides and antimonides cover with their bandgap the near-infrared spectral range including the important optical C-band (1.55 µm) for fibre-based communication. Based on these materials, we fabricate heterostructures with novel physical properties, especially carrier confinement in one or 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 nanometer 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 (2×2 µm²) of InAs quantum dots with low areal density on a GaAs(100) surface.*

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.

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.

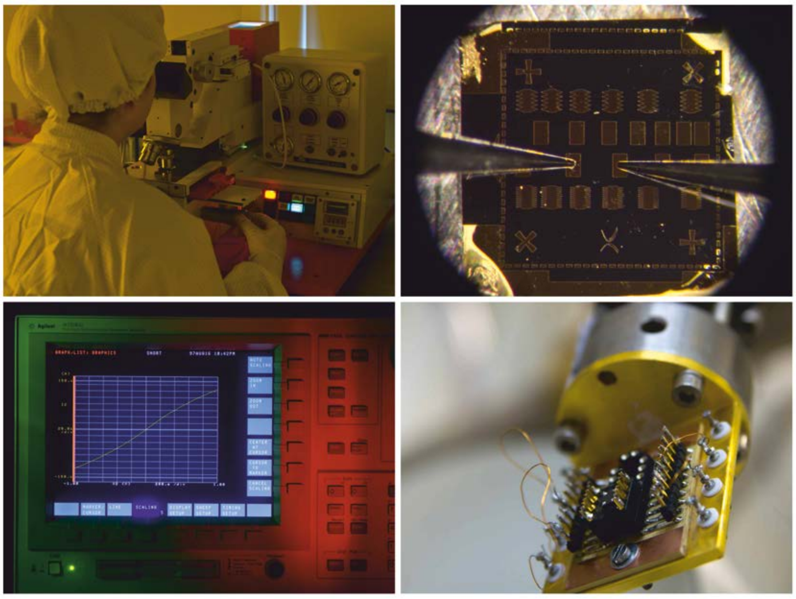



*GaAs/AlAs micropillar cavity with embedded InAs quantum dots and inter-cavity contacts. (UPB, AG Reuter)*

We also nanopattern the heterostructures into device prototypes for more sophisticated experiments, e. g., in the field of quantum information technology. This includes low-capacitance diodes for ultrafast switching and micropillar cavities. As methods electron beam and optical lithography as well as wet and dry etching processes are employed.

## 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)*

## Equipment & Methods

- Molecular beam epitaxy systems for III-V compound semi-conductors
- 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
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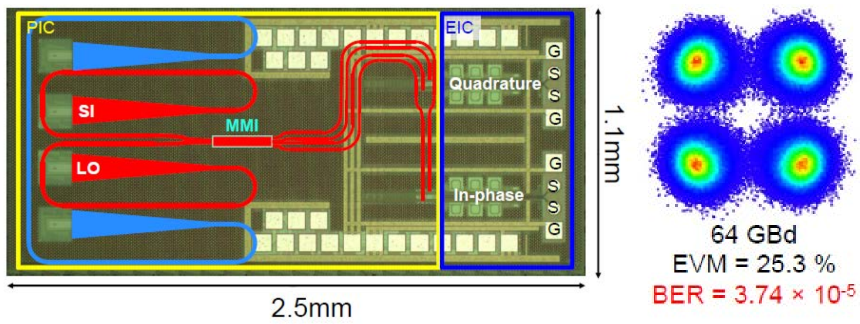
In recent years photonic integration technologies (Silicon Photonics, Indium-Phosphite, Lithium Niobate on Insulator, Silicon Nitride, and others) have made tremendous progress. Photonic integration offers for the first time the possibility to combine optical devices together with digital processors, memory, and software on a single chip. It allows for complex, miniaturized photonic circuits, close proximity of photonics and electronics, and reduces energy consumption and size. Photonic integration allows to break up the paradigm of separate domains of photonic and electronic signal processing and makes it necessary to rethink fundamentally how e.g. algorithms, processors, or communication systems should be optimally designed. Besides mathematical analysis, a major challenge in photonic-electronic systems lies in a model-driven, cross-domain design methodology. We use diverse modelling techniques to model photonic, digital, analog, and radio frequency signals and devices. These models are used in a mixed-mode simulation environment for photonic-electronic co-simulation and joint optimization of photonics and electronics. In our research we model, simulate, and design integrated electronic-photonic systems. The circuits are fabricated using photonic integration platforms offered by academic and commercial foundries. After fabrication we build and characterize experimental systems. Currently our focus is on fiber-optic communications, optical analog-to-digital conversion and digital-to-analog conversion, microwave and THz photonics, and photonic quantum computing.

## Broadband electronic-photonic circuits for optical communication

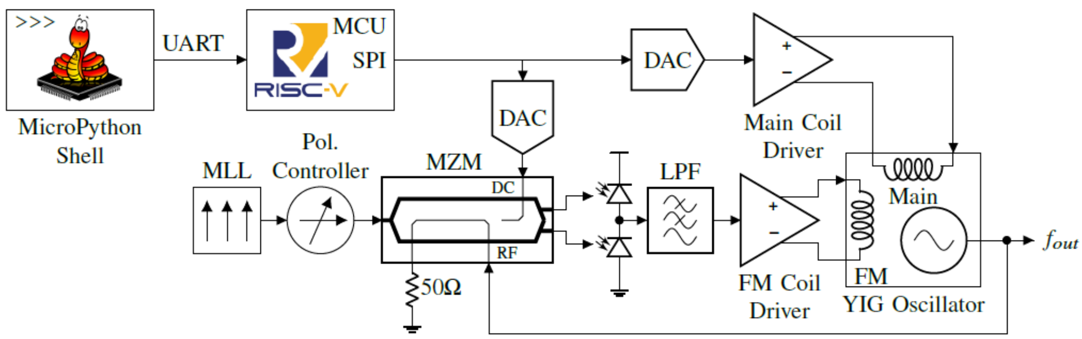
Optical fibers offer THz of signal bandwidth, which is much more than current lasers, modulators, photo detectors or broadband electronic ICs can achieve. Hence the opto-electronic and electronic circuits usually come as the major bottleneck in optical communication systems. The design of extreme broadband 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. A co-design approach comprising electronic circuit design and simulation, optical device modeling, and high-frequency and passives simulation is required to achieve optimal 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. In 2018 we realized an optical receiver with record data rate in silicon photonics technology, achieving 128 Gb/s which was published on Optical Fiber Conference (OFC) in San Diego.

*(Left) Microphotograph of silicon photonics chip monolithically integrating a homodyne receiver, differential photodetectors for in-phase and quadrature signals, and high-speed transimpedance amplifiers. Chip size is 1.1mm x 2.5mm. (Right) Measured 64 GBaud (128 Gb/s) signal. EVM, error vector magnitude; BER, bit error rate.*



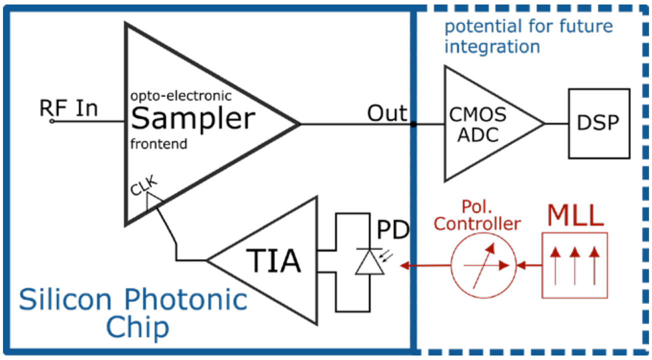

## Electronic-photonic RF and THz signal generation with very low phase noise

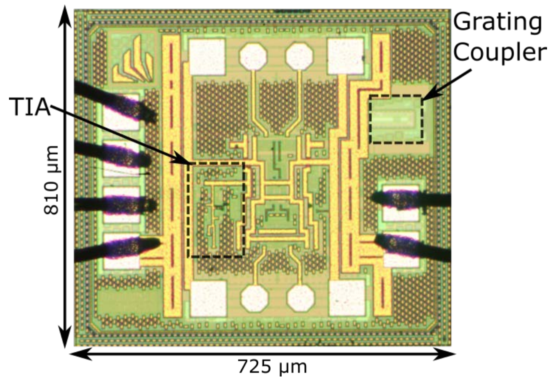
Mode-locked lasers (MLLs) enable the generation of ultra-short optical pulses and high peak powers. In addition, they offer frequency-stable pulse repetition rates with exceptionally low jitter down to a few attoseconds. This makes MLLs generally suitable for frequency synthesis with superior phase noise. We investigate different frequency synthesizer architectures for MLL-based RF and THz frequency synthesis such as locking electronic oscillators to MLLs, injection-locking of CW lasers to optical frequency combs and photomixing them to RF and THz frequencies and others. Fig. 2 shows an optoelectronic PLL in which a microwave oscillator is locked to an MLL by means of an electro-optical phase detector built from an MZM and differential photodetectors. Such synthesizers can achieve a jitter which is at least one order of magnitude better than the best electronic laboratory-grade RF signal generators at similar frequency tuning range and frequency resolution.




*Optoelectronic PLL using electro-optical phase detector. MCU, microcontroller unit; MLL, mode-locked laser; MZM, Mach-Zehnder modulator; Pol. Controller, polarization controller; LPF, low pass filter; YIG, Yttrium Iron Garnet.*

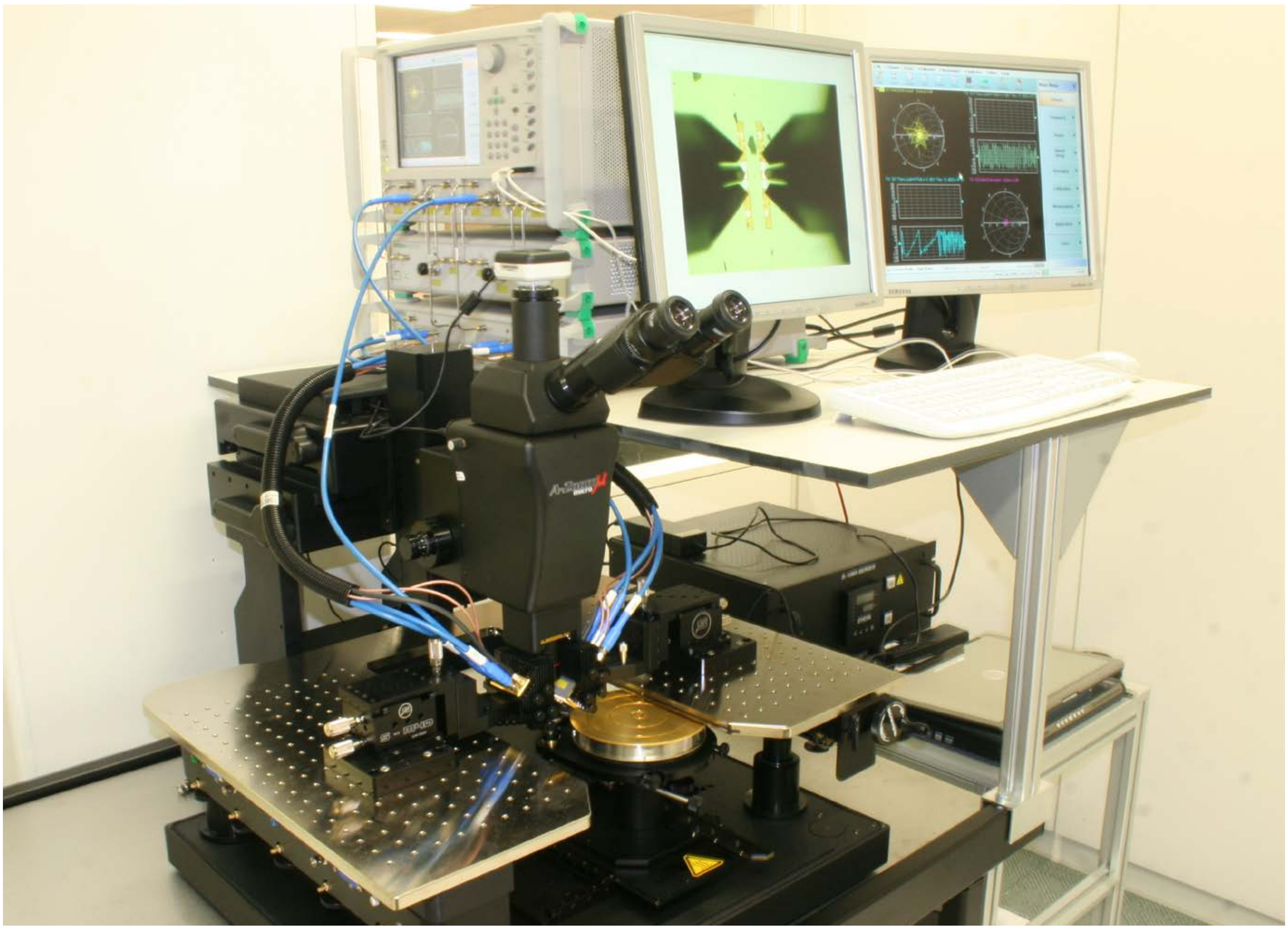
## Photonic analog-to-digital and digital-to-analog converters

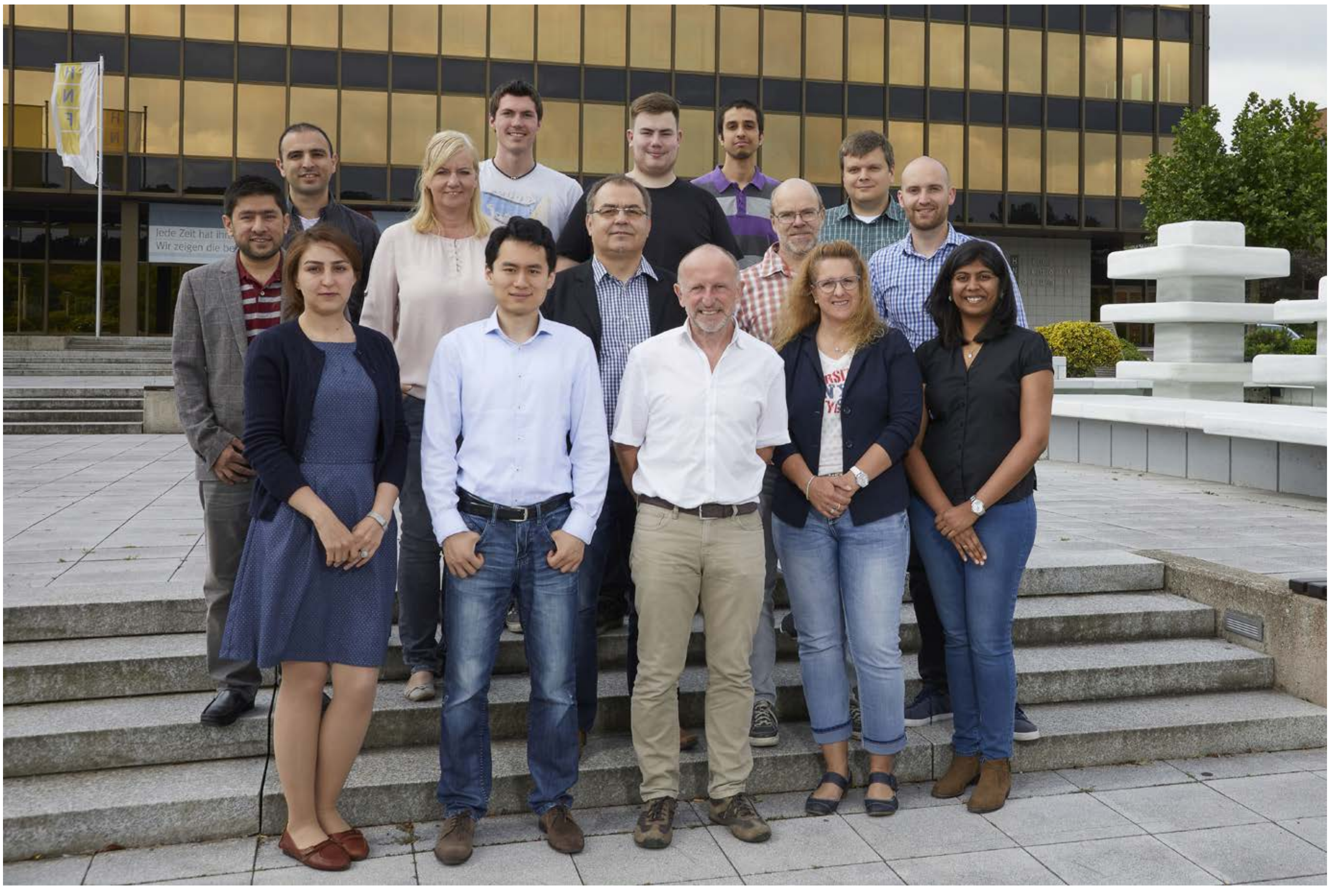



*(Left) Simplified block diagram of photonic sampler. (Right) Microphotograph of photonic sampler chip in silicon photonic technology. Chip size is 0.725mm x 0.810mm.*

Photonic analog-to-digital converters (ADCs), which perform optoelectronic sampling using ultra-stable optical pulse trains from MLLs, have been investigated for many years. They represent a promising approach to overcome the bandwidth and resolution limitations of purely electronic ADCs. With the recent progress in silicon photonics technology, monolithically integrated photonic ADCs become feasible. We investigate ultra-broadband photonic ADCs using time-interleaved and frequency interleaved sampling techniques and implement electronic-photonic ADC chips with high bandwidth and resolution. Besides photonic ADCs we also investigated photonic digital-to-analog converters (DACs) with high bandwidth and high resolution with the target to allow for much increased data converter bandwidth for future communication and signal processing systems.





## Equipment & Methods

- Design of electronic-photonic integrated circuits (SOI CMOS, SiN, LNOI)
- Modeling and co-simulation of photonic, analog, RF, and digital circuits
- Comprehensive design environment (Cadence, Mentor, Lumerical, CST, Empire, Keysight, Synopsys) for photonic and electronic IC design
- RF Lab for characterization electronic ICs up to 125 GHz
- Photonic Lab for photonic IC characterization up to 70 GHz modulation frequency
- Inhouse assembly and bonding equipment for fast prototyping

# Many-Body Theory of Solids
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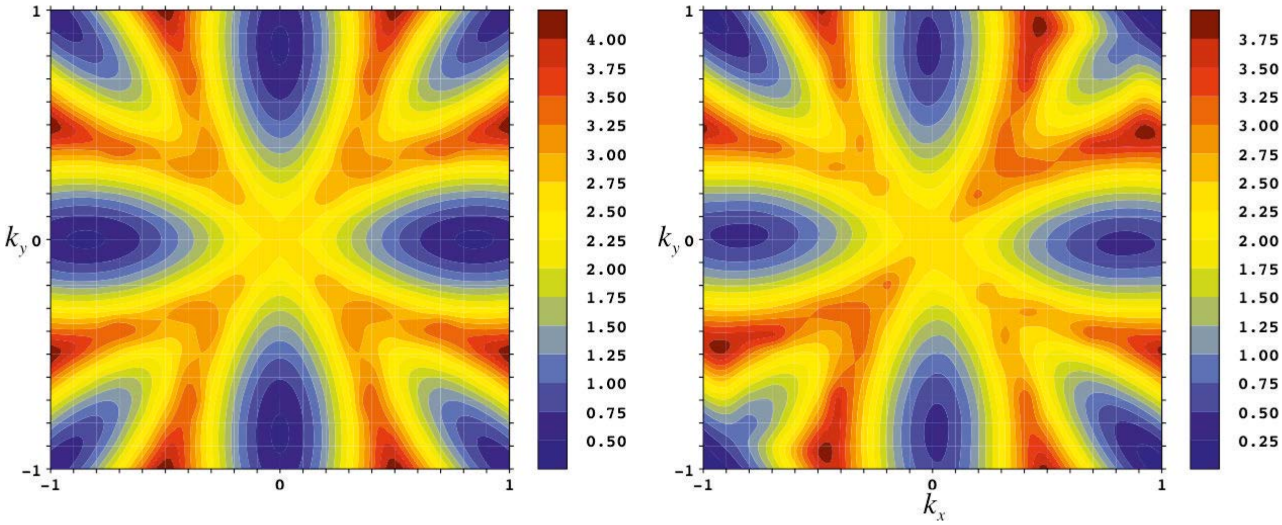
Accurate quantitative predictions of the optical, electronic and magnetic properties of materials are possible with a combination of modern ab initio quantum-mechanical methods and large-scale numerical calculations. From microscopic simulations of the dynamics of electrons and atomic nuclei in the presence 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.



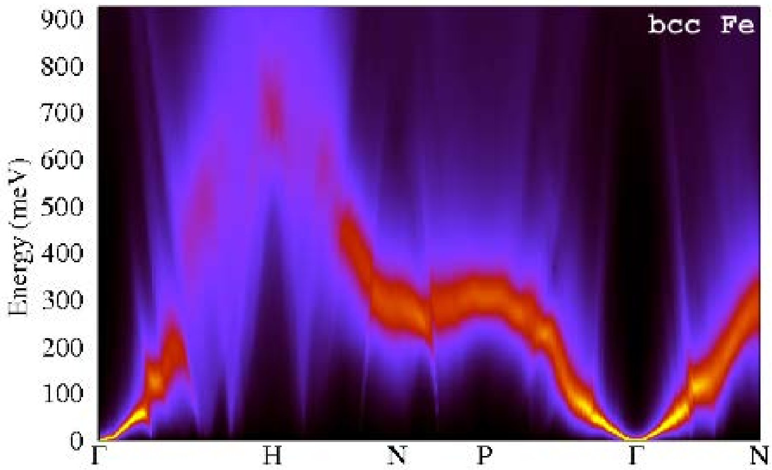

*Energy dispersion of the lowest conduction band of silicon without strain (left) and with 3% uniaxial strain along the [110] direction (right).*

## 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

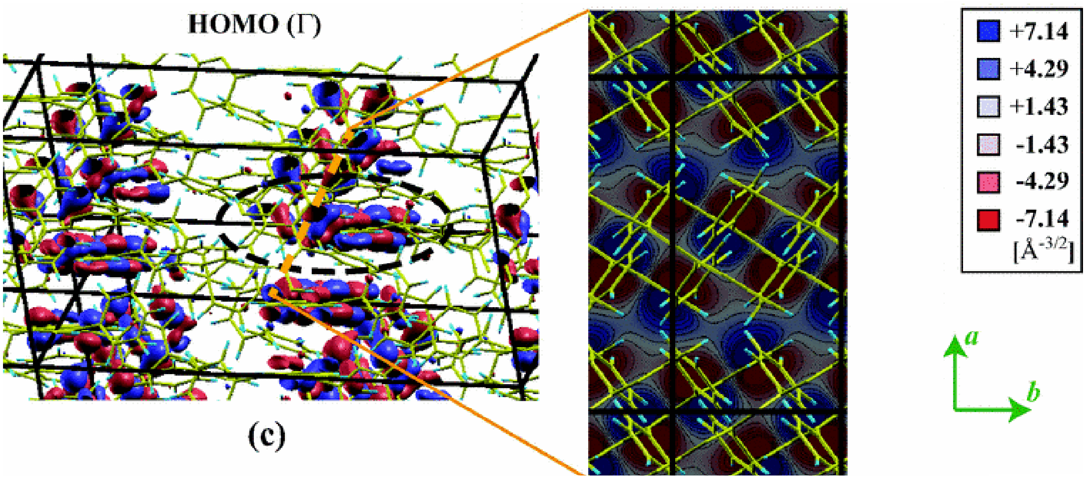
Compared to traditional electronic devices, whose functionality relies crucially on charge transport, spintronics constitutes a promising new concept where information is encoded in the electron spins. As these can be manipulated by external fields without physical transport, much faster switching times 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.*


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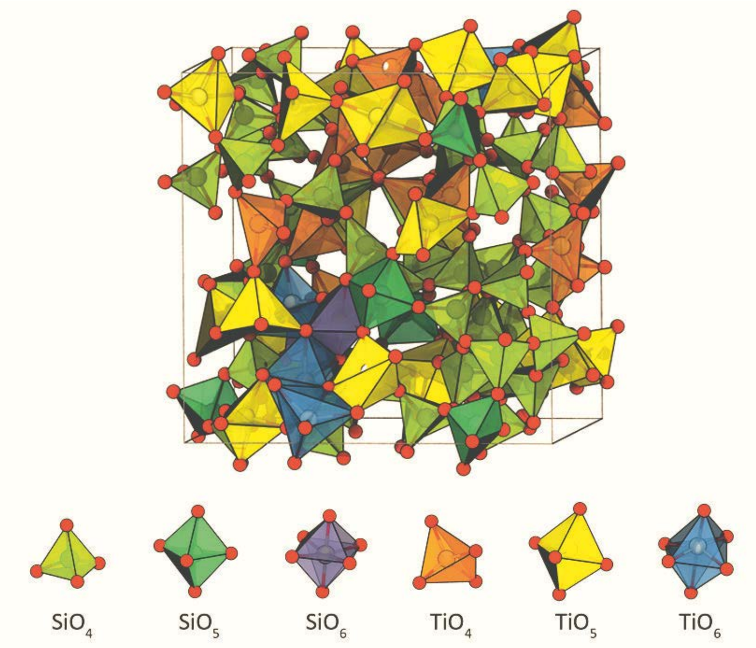
We employ density-functional theory and Green function methods in order to predict and understand a wide range of materials properties. For example, we are interested in atomic geometries, electronic and optical excitation spectra, phase transitions and electron transport properties. Solid surfaces,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

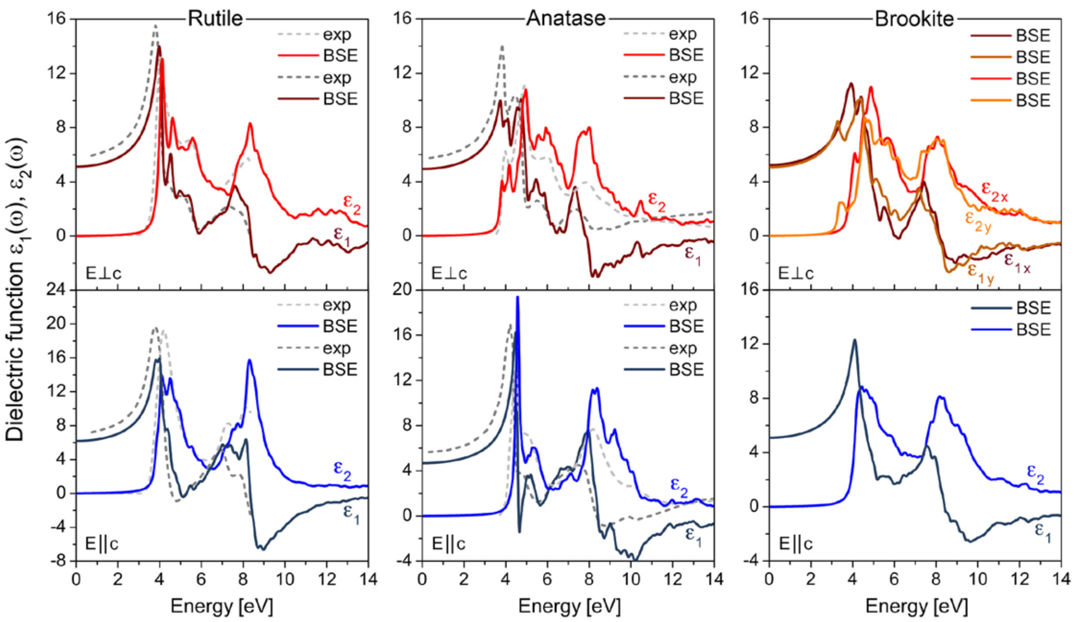
## Ground-state properties

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.



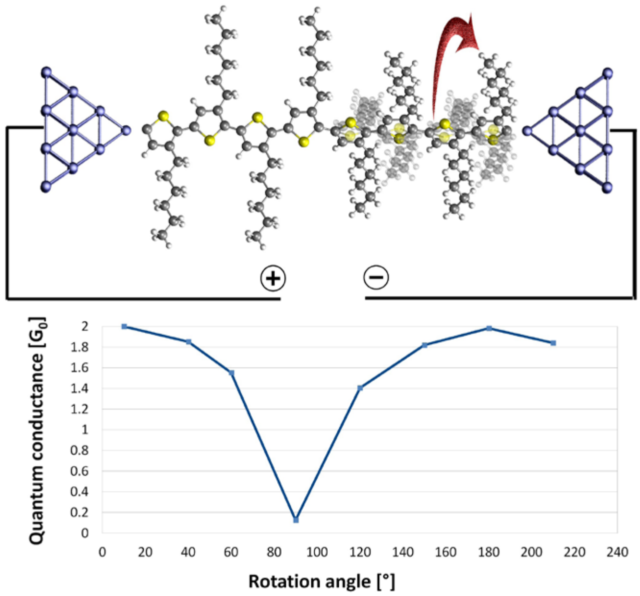

*Calculated geometry of amorphous $Ti_{0.4}Si_{0.6}O_2$ in coordination polyhedra representation.*

## Spectroscopic signatures




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

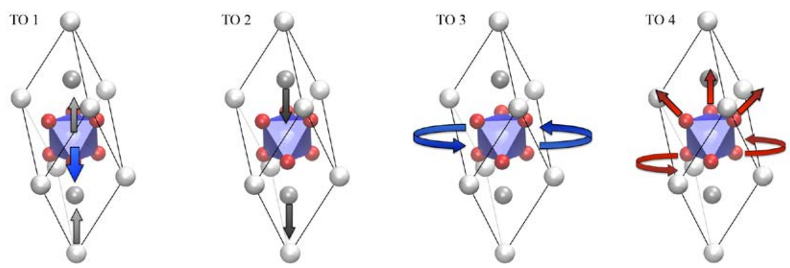
The calculation of excited states and their properties requires extensions to DFT. Accurate excitation energies may be obtained from propagator or Green function approaches. They start from the screening response of the electronic system after electronic or optical excitation. Accordingly, the dynamically 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.

## Equipment & Methods

- First-principles electronic structure theory

# Theory of Functional Photonic Structures

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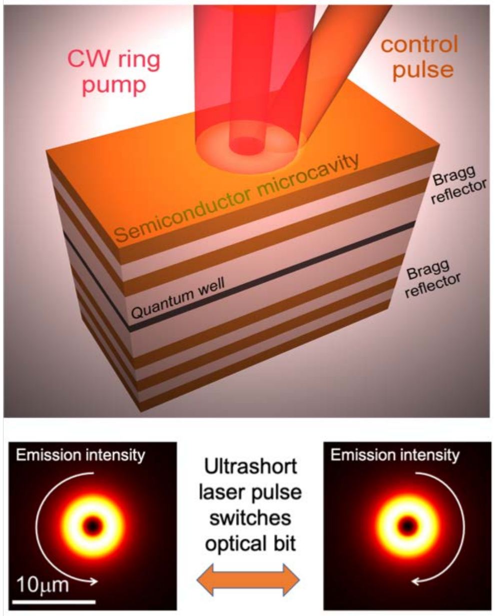
Nanostructured semiconductors nowadays play a crucial role in optoelectronics and photonics and have become indespensible in our everyday life. The optical properties of such systems are determined by complex excitations inside the material, the details of which can often not be understood with simple 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 ex- citation 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.

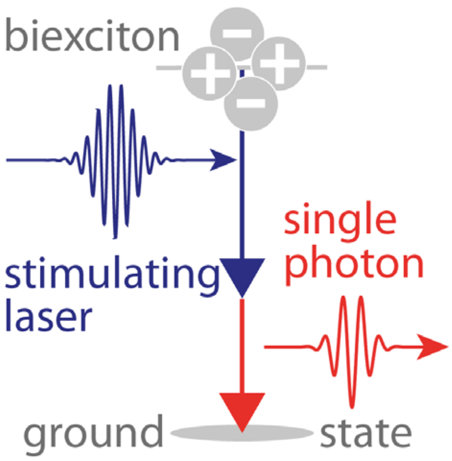



*Novel concept for the ultrafast all-optical control of an optical bit. Information is stored in the rotation direction of the polariton vortex. (UPB, Xuekai Ma)*

## Nonlinear photonics of semiconductor nanostructures

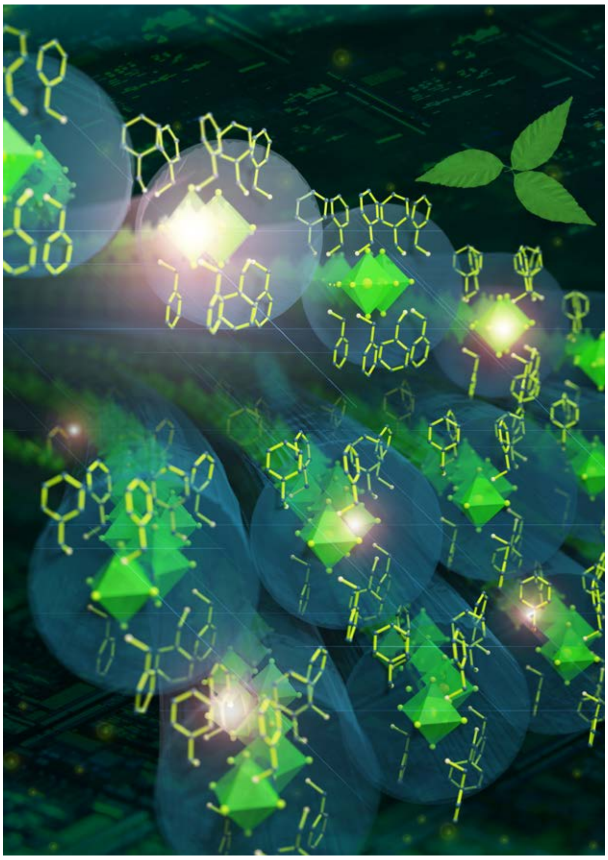
In the area of photonics, in addition to the design of the electronic states of a given nanostructure, we aim to also design the propagation of light through the system. We are particularly keen to study optical excitation schemes in which the system behavior can be controlled all-optically and in which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

One system of particular current interest for us are planar semiconductor microcavities in which the strong coupling of an optically active material (e.g., excitons in semiconductor quantum-wells or molecular crystals) 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 suppress 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. Our recent studies also include the exploration of such systems as a quantum resource in quantum information processing.




*Scheme for the optically controlled generation of single photons from a semiconductor quantum dot. (UPB, Dominik Breddermann)*

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 is 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.

*Artistic sketch of a novel type of hybrid perovskite semiconductor material that was exfoliated into single ultra-thin layers. (Universität Gießen, Elisa Monte)*

## Photophysics of molecular and hybrid materials

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

In this area we investigate 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. 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 molecular doping, photogeneration of charges, and exciton dynamics in molecular films. Besides disordered organic films, our recent studies also include crystalline hybrid organic–inorganic semiconducting perovskites and two-dimensional semiconductors.

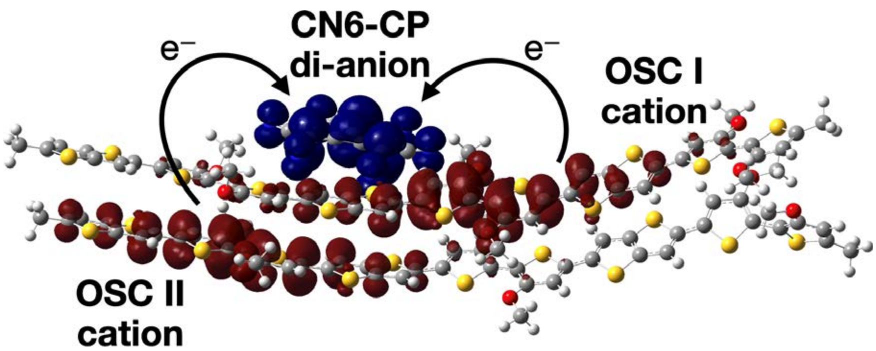



*Illustration of molecular p-type double doping in which two charges are transferred from the organic semiconductor host material onto a single doping molecule (UPB, Thomas Bathe).*

## Equipment & 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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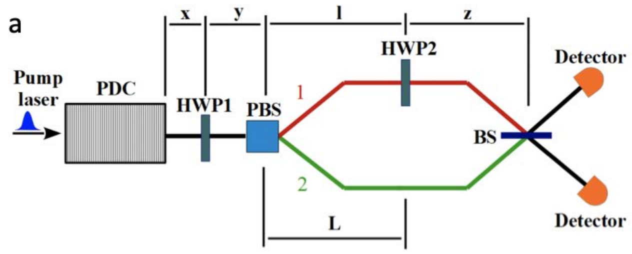
In general, photons are excellent information carriers because of their high speed, weak interaction with the environment, and many schemes and methods for controlling their properties. Photonic qubits and entangled photons are the basis of quantum information protocols and algorithms, quantum cryptography and quantum computing.

The Theoretical Quantum Optics group is focused on the study and design of quantum states of light with unique properties and the development of their applications for quantum computing, quantum metrology and matter – quantum light interaction. We study a wide range of quantum states of light, from biphoton pairs to bright squeezed states, generated in various nonlinear systems. Using our methods and approaches, we explore the properties of quantum light and its correlations. Our research includes multiphoton quantum linear and nonlinear interferometers which have a lot of benefits compared to their linear counterparts in improving phase sensitivity and creating hyperenetangled states of light. In addition, we investigate various integrated photonic systems and develop theoretical approaches to describe the generation, propagation and manipulation of quantum light in such systems. Finally, we explore an interaction of atoms and semiconductor quantum wells with various quantum states of light and study new phenomena arising from such interactions.

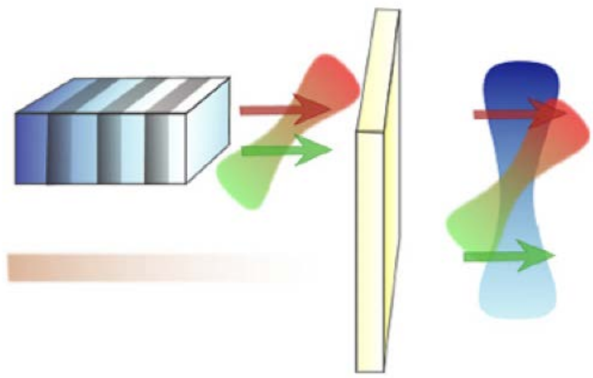
## Multiphoton interference. Hyperentanglement.

The two-photon interference or Hong-Ou-Mandel (HOM) interference is well-known quantum effect which takes place when two indistinguishable photons come to different ports of a balanced beam splitter. HOM interferometry is widely used to measure the degree of indistinguishability of photons and provide picosecond time resolution. In contrast to two photons, four-photon interference has more complicated interference pattern and strongly depends on the number of temporal modes: An anti-bunching behavior in the four-photon interference pattern becomes more pronounced with an increase in the number of temporal modes.




*A schematic setup of the extended HOM interferometer with the parametric down-conversion (PDC) source, beam splitter BS, polarization beam splitter PBS, half-wave plates HWP.*

Entanglement is a unique property of quantum systems that underlies the quantum information protocols and algorithms. However, when dealing with huge amounts of data and large quantum systems, the simplest pairwise entanglement becomes ineffective. To reduce the number of operations and increase the effectiveness of highly multidimensional systems, multidimensional entanglement and hyperentanglement, combining quantum correlations in different degrees of freedom, are strongly required. Such states are characterized by a large multidimensional basis and pave the way for new applications and technologies which are not feasible in the case of a single degree of freedom.



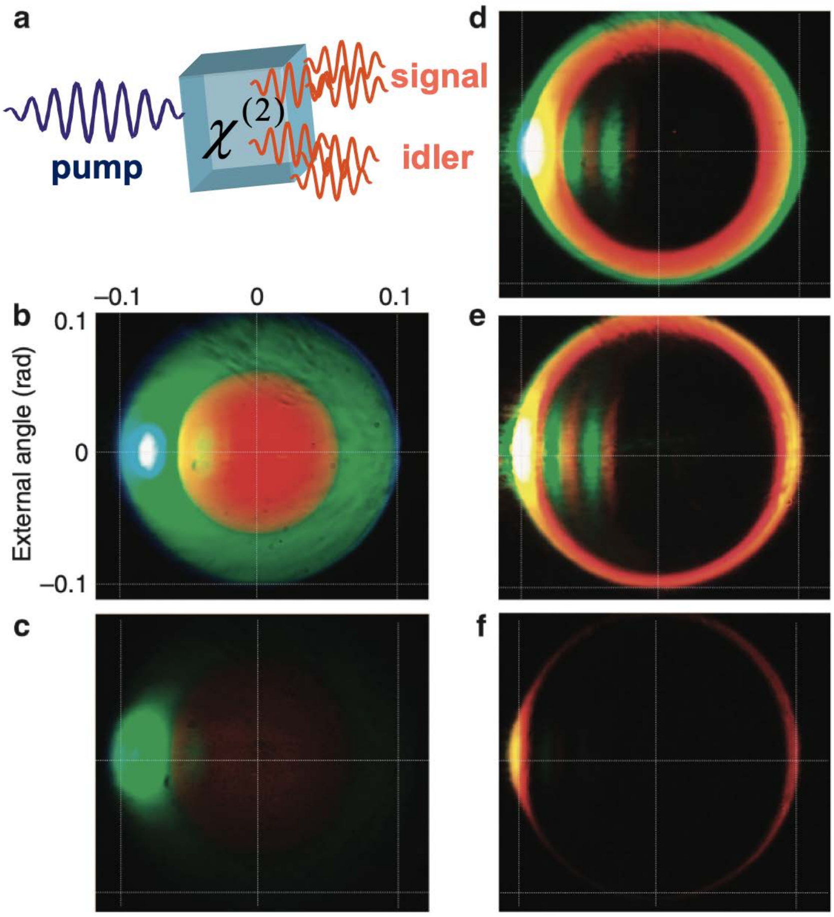
*Two photons generated in a PDC process have strong frequency correlations. The creation of spatial entanglement between photons leads to a hyperentanglement generation which results in novel features in the coincidence probability.*

We investigate the generation of multidimensional entanglement and hyperentanglement in extended quantum HOM interferometers involving multiphoton interference. We explore the creation of specific quantum states of light, such as multidimensional Bell states, etc., in such quantum interferometers and develop integrated versions of them with optimized parameters.

## Bright squeezed vacuum (BSV) states of light

Bright squeezed vacuum is a macroscopic nonclassical state of light with strong correlations between generated signal and idler beams. BSV has a huge number of photons per mode (1013) and macroscopic correlations together with noise reduction and phase sensitivity below the classical limit. This makes such states of light very attractive for a variety of quantum applications, including quantum metrology, quantum sensing, quantum imaging, etc. However, a theoretical description of BSV is challenging because it involves many photons and depends on time ordering effects.

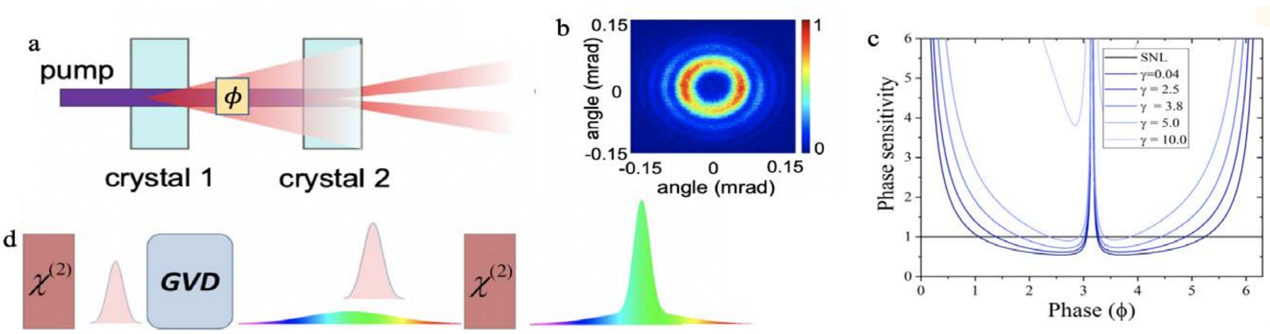
Using different approaches, we investigate the spatial and frequency properties of BSV and its macroscopic correlations. We study various schemes of BSV generation, the mode structure of the generated radiation, properties of BSV with increasing parametric gain, walk-off effects, generation of high-order orbital angular momenta in BSV and their strong correlations, etc.




*A scheme of the BSV generation and snapshots with a photographic camera which show the spectra of high-gain PDC at different crystal orientations.*

## Nonlinear SU(1,1) interferometer

A nonlinear SU(1,1) interferometer can be constructed from the linear Mach-Zehnder interferometer by replacing beam splitters with nonlinear media in which the parametric down-conversion (or four-wave-mixing) process takes place. These types of interferometers have many advantages over their linear counterparts in terms of resistance to external losses and improving phase sensitivity: even with a vacuum input, such interferometers can overcome the classical phase sensitivity bound. In addition, SU(1,1) interferometers are powerful tools for spectral engineering, radiation shaping and high-order orbital angular momentum generation. We study the spatial and frequency properties of multimode SU(1,1) interferometers in various configurations and design their fully integrated versions based on different integrated platforms.




*a) A schematic representation of the SU(1,1) interferometer. The radiation from the first crystal acquires some phase and is amplified in the second crystal. b) At some distance between the crystals, it is possible to obtain the ring-like spatial intensity distribution containing orbital angular momentum modes with non-zero orbital numbers. c) The phase sensitivity of the SU(1,1) interferometer normalized to the shot noise limit (SNL) for different gains of the process. d) Spectral engineering using the SU(1,1) interferometer. The broadband PDC light generated in the first crystal is stretched and chirped during its propagation in a group velocity dispersion (GVD) medium. In the second crystal, this pulse is again overlapped with the pump and is amplified, that leads to a narrowing of the spectrum.*

## Equipment & Methods

- Schmidt-mode approach based on independent collective broadband photonic modes
- Method of integro-differential equations for operators to describe macrocorrelations in bright states of light
- Generation of hyperentanglement within linear and nonlinear interferometers
- Simulation of generation and propagation of light in integrated photonic systems with losses and imperfections
- Full quantum theory of light-matter interaction

# Integrated Quantum Optics
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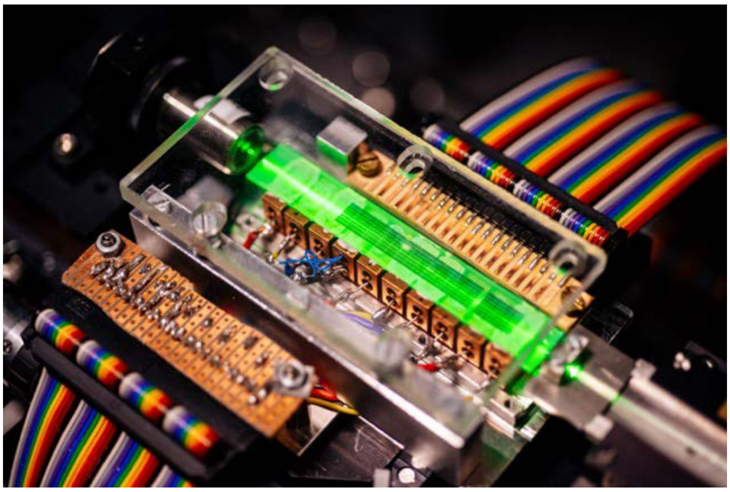
The integrated quantum optics group (IQO) investigates new photonic systems for applications in quantum information processing and studies fundamental questions of quantum theory. On the technological level our goal is, on the one hand, to develop quantum devices for practical applications such as quantum communication and metrology, and on the other hand, to implement large photonic networks, which can be used, e.g., for photonic quantum simulators. From the fundamental perspective we explore the quantum character of light and networks by studying particle-like and wave-like properties, as well as the time-frequency properties of quantum states and measurements.

In our experiments we use tailored integrated optics, pulsed light, time-multiplexing and photon-number resolving detection. Our integrated optic devices reduce significantly the experimental effort for realizing quantum light sources and large quantum circuits. This, in turn, enables the implementation of complex high-dimensional systems and the exploration of novel photonic quantum systems and new physics combining ideas from quantum physics, ultrafast optics and quantum information science.

## Quantum networks

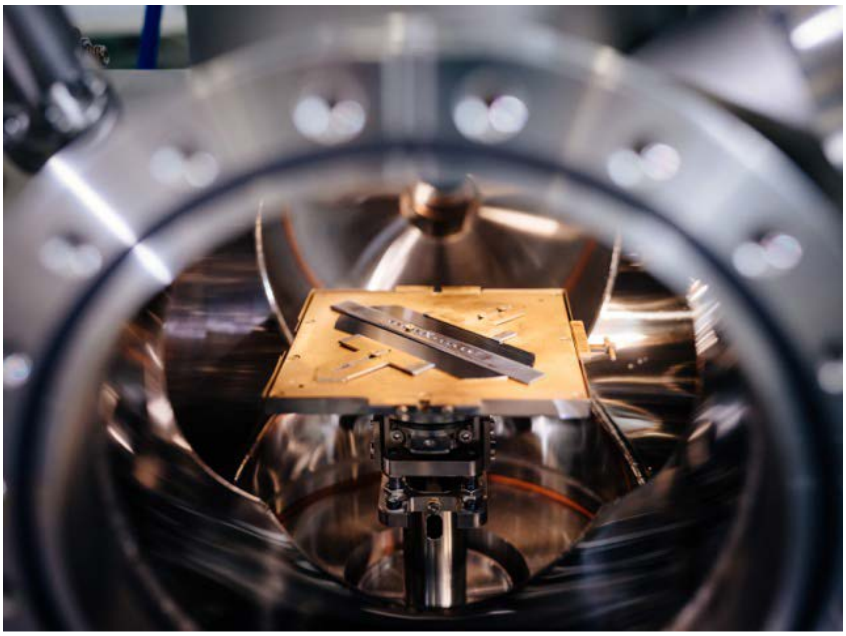
When aiming for the implementation of large-scale photonic quantum networks, one soon realizes that the demanding requirements on the different building blocks as well as the need for scalability limit the maximum size of practical systems. Integrated architectures provide an attractive solution to this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



*Picture of our HOM-on-a-chip sample, which integrates a hallmark quantum optics experiment. (UPB, Besim Mazhiqi)*

To this end, we are developing tailored sources and quantum circuits for the generation and manipulation of photon pairs and squeezed light based on non-linear waveguides. These allow for accurate control of the temporal-spectral properties of the generated pulsed photons, which are essential building blocks for large quantum networks and for high dimensional information encoding based on temporal modes. In this context we have also pioneered the development of a new device, the quantum pulse gate, which opens unique possibilities for high-dimensional quantum communication and quantum-limited time-frequency metrology applications.

In recent years, we have introduced time-multiplexing as a valuable method for studying quantum walks, which offer the basis for flexible and efficient quantum simulation. Quantum walks describe the coherent propagation of quantum particles in a discrete environment and are ideal for exploring the role of classical and quantum interferences in networks. We employ our efficient photon number resolving detectors for benchmarking state-of-the art photonic quantum systems that target mesoscopic scales. Based on our experimental know-how we also propose and demonstrate new theoretical concepts, such as Gaussian Boson sampling or photonic networks with active feedback and feed-forward, which are key ingredients of future photonic quantum computers.



*A sample in the vacuum chamber of our sputtering machine. (UPB, Besim Mazhiqi)*

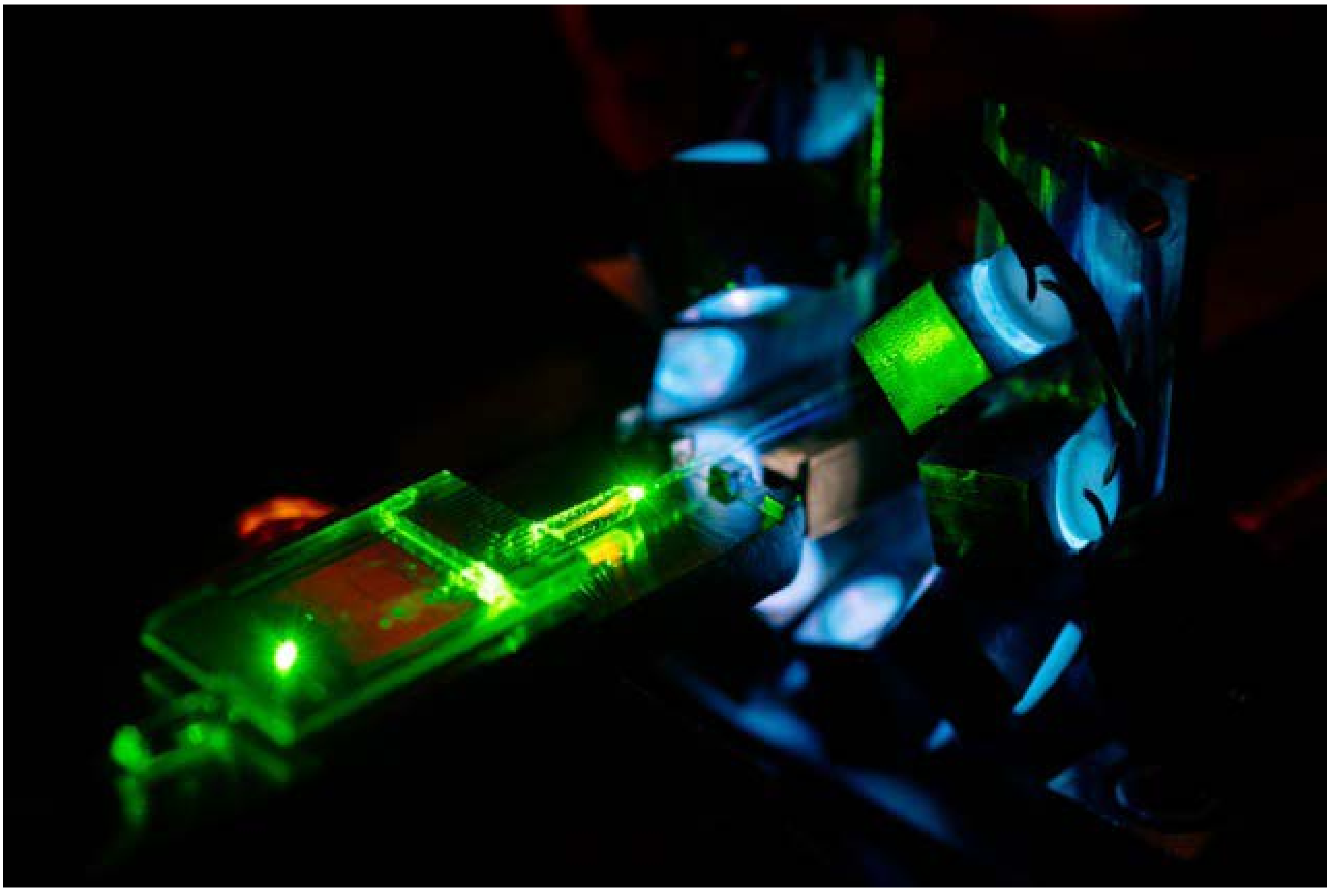
## Integrated quantum devices and technology

We fabricate integrated waveguide structures and novel devices based on periodically poled LiNbO3, LNOI and KTP and develop new key components towards practical applications of photonic quantum technologies. Our devices provide multiple on-chip functionalities and feature, in particular, robustness, miniaturization and outstanding control, such as fast electro-optic switching.

An example of our recent work is the development of sophisticated two photon interference experiment where we integrated a full HOM experiment on chip. In this system we have combined a parametric down-conversion source and an adjustable interferometer including as an electro-optically controlled delay line on a single monolithic structure. Furthermore, we develop new integrated SU(1,1) quantum interferometers, quantum wavelength converters to bridge the gap between visible and telecommunication wavelengths and hybrid systems, which combine our waveguides with other integrated platforms.

To improve the performance of existing engineered parametric down-conversion sources, we also work on the development of high-quality waveguides using periodically poled KTP. Here we explore diced ridge waveguides as well as rubidium exchanged channel waveguides for achieving optimized quantum performance benchmarks.

Current research activities concentrate towards the establishment of thin-film lithium niobate (LNOI) for the implementation of future quantum technologies. Here, we harness our expertise for the engineering of non-linear structures to accomplish the implementation of innovative quantum circuits and devices with unique compactness and performance.



*Pigtailing. Optical fibres are attached to our samples to provide hands-off operation. (UPB, Besim Mazhiqi)*

## Equipment & Methods

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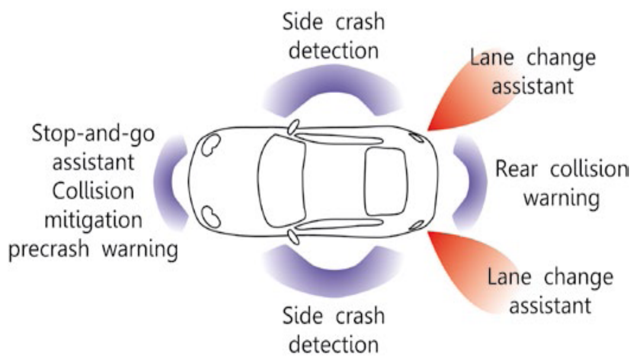
The High-Frequency Electronics group is mainly focused on the design of monolithically integrated circuits for applications in the high frequency domain, in particular for optical communications and sensorics.

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- and GaN-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 was also development in a DFG-project. In the Collaborative Research Center TRR142, the group contributed high-speed electronic circuits for quantum mechanical experiments.

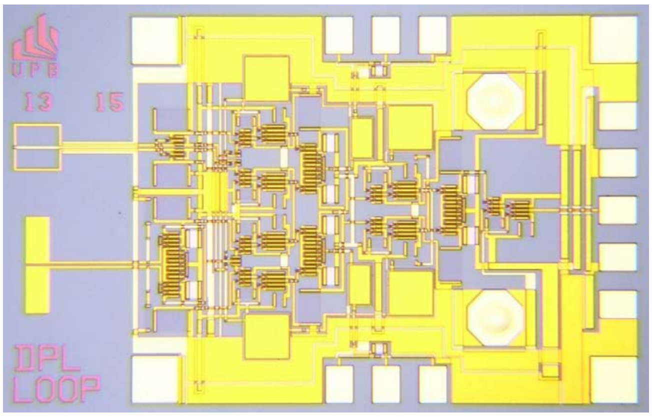
## 24 GHz Car Radar

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 develoment 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

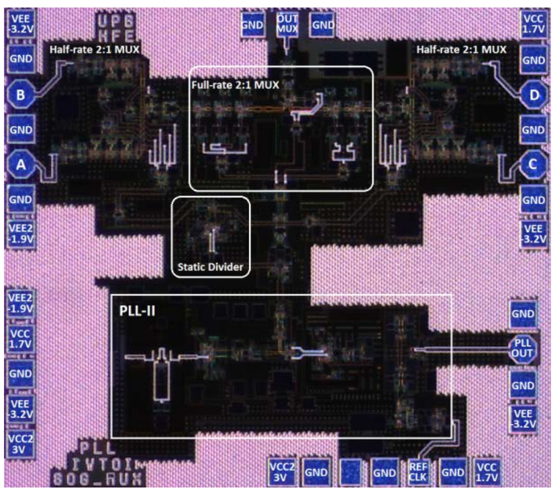



*Magnetic/Electric Field Double Probe*

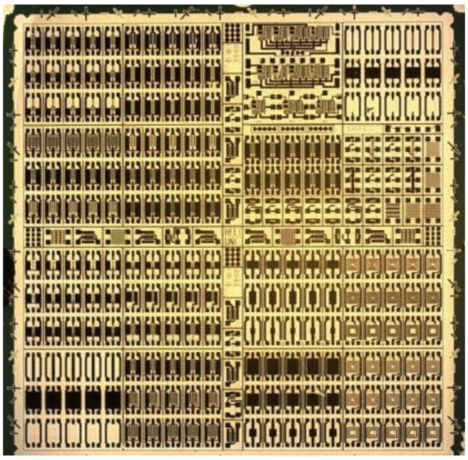
Near-field measurements of PCBs and large-scale integrated circuits are gathering increasing interest for a better understanding of EM field distribution and respective EMC issues from the very beginning of the design process. Due to fine geometries of today's PCBs or even ICs, small field probes exhibiting 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 Disper-sion (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*



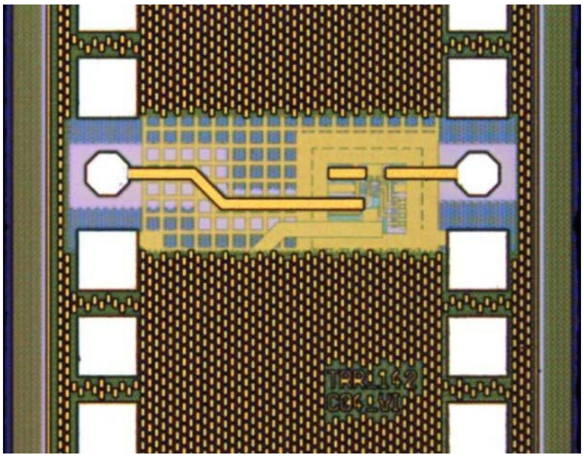
RF Test Field

## Flexible RF Electronics for Communication

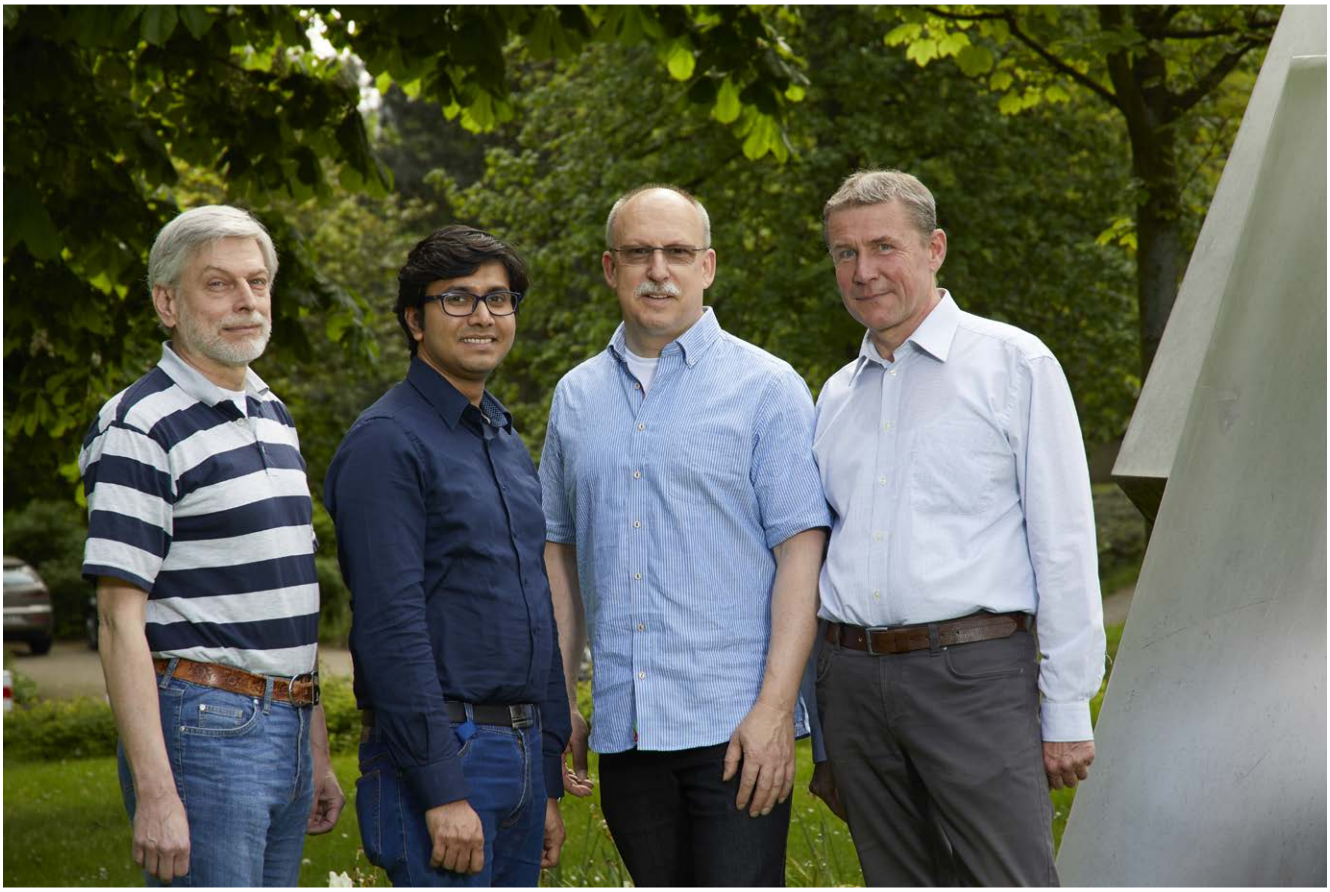
In the DFG Priority Program FFlexCom, University Paderborn collaborated with University Leipzig, Germany, in the development of basic analogue and digital circuit blocks for flexible communication electronics based on amorphous ZnO. The adjacent micrograph represents the RF test field, which allows high-frequency 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.

## Pico-second Pulse generator for Quantum Physics

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 have been achieved in such circuits. These circuits also allow for the tuning of pulse width and amplitude. Fabricated chips were used to perform ultrafast coherent phase control experiments in quantum dots.



Pico Second Pulse Generator



## Equipment & Methods

- 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
- 20 GHz Spectrum Analyzer
- 110 GHz Signal Generator
- 110 GHz Wafer Prober

# Ultrafast Nanophotonics

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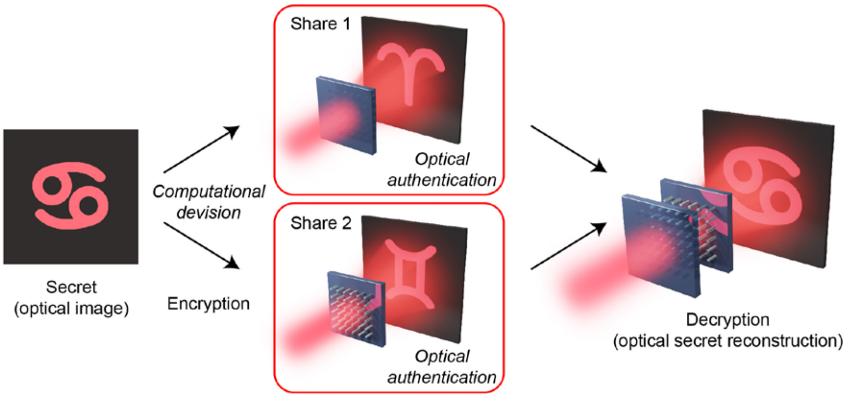
The Ultrafast Nanophotonics group at the University of Paderborn focuses its research on the optical properties of artificial nanostructured material systems. Modern nanotechnology opens the possibility to manipulate the arrangement and structure of natural materials down to the nanoscale to sizes comparable to the optical wavelength. This freedom allows 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 for compact optical devices



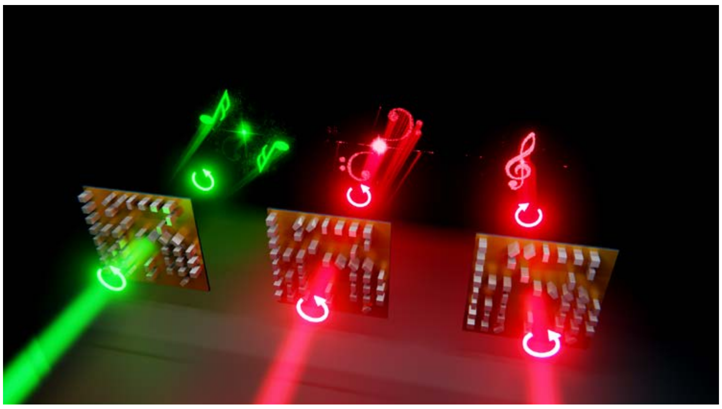
*Optical secret sharing by using two cascaded metasurfaces*

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. However, 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 strongly localized fields in dielectric and metallic nanostructures the effective material parameters can be nearly arbitrarily altered and in that way, new optical materials can be 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 include dual-polarity lenses that are switchable from focusing to defocusing and high-resolution holography that can provide new concepts for optical secret sharing applications of single-photon manipulation.


*Realization of 3D holograms*

## Tailored light-matter interaction for nonlinear photonics

Active photonic devices require a strong interaction of light with matter that can lead to nonlinear optical effects. However, such nonlinear optical processes are in general weak and limit the functionality for many compact or on-chip applications. In particular, phase matching conditions have to be fulfilled to increase the efficiency along with the propagation distance. Fortunately, plasmonic and dielectric nanostructures and nanoantennas can show a very strong light-matter-interaction and, therefore, lead in addition

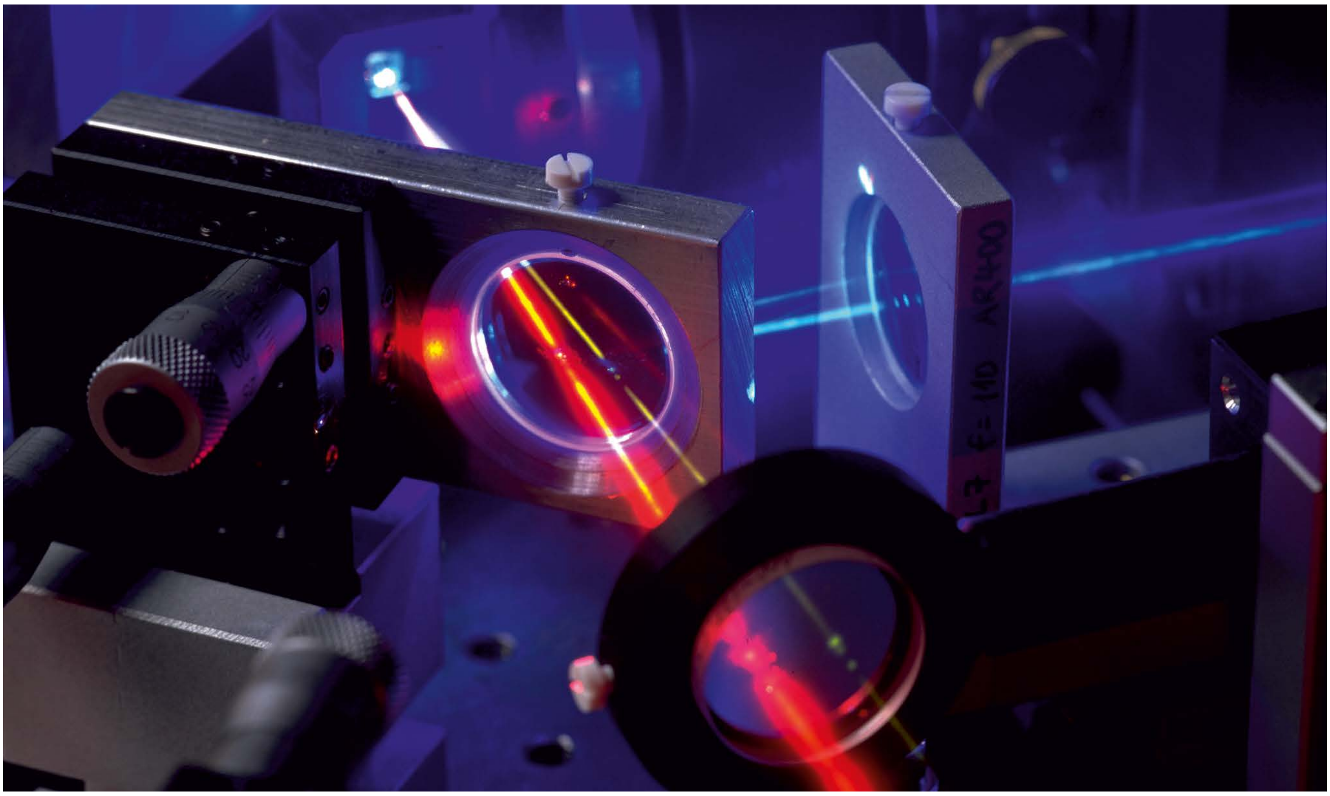

*Metamaterial with designed light-matter interaction for tailored nonlinear optics*

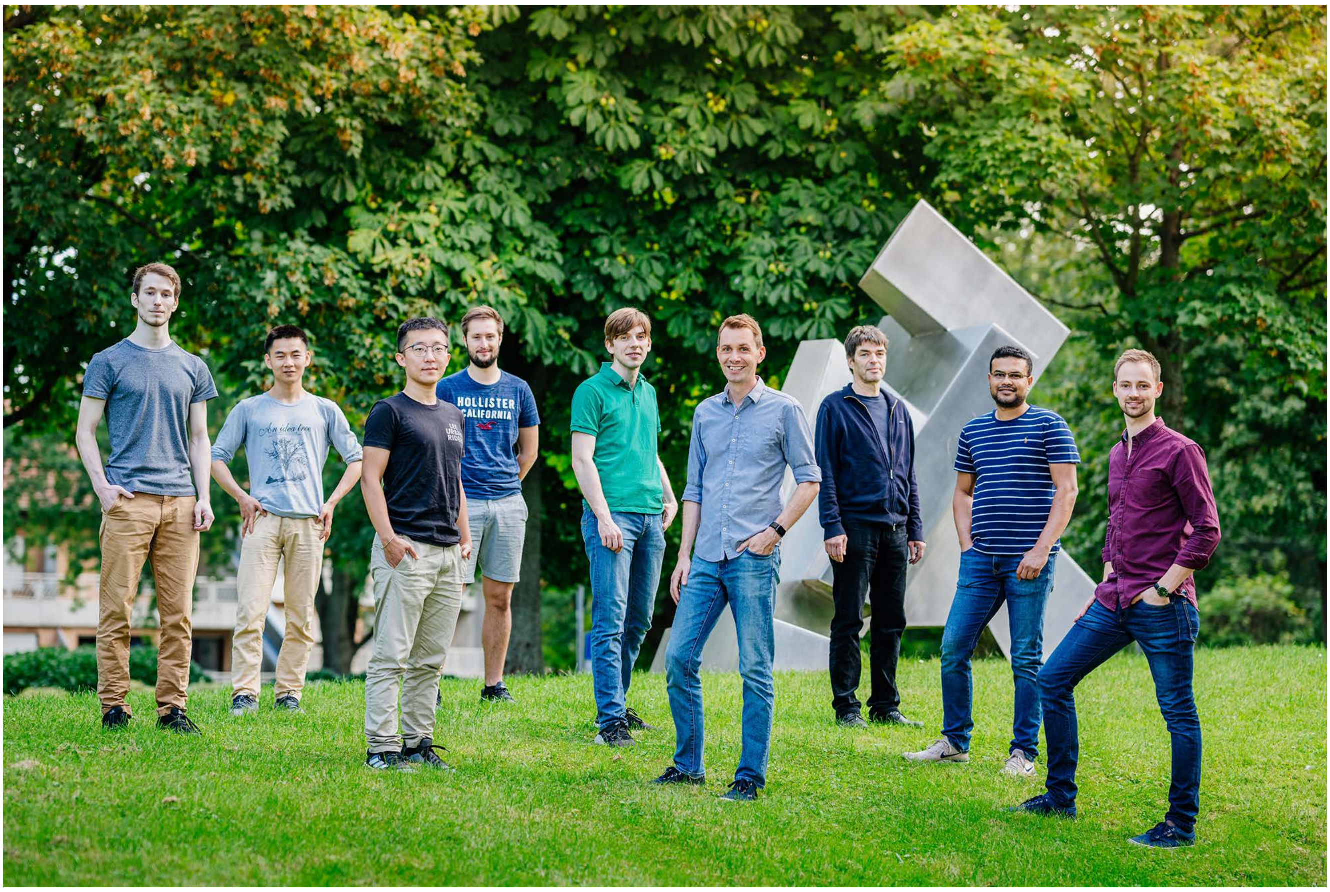
to a field enhancement in their proximity. This makes them well suited for nonlinear optical processes. The Ultrafast Nanophotonics group develops and tests various concepts for enhancing the nonlinear processes and at the same time tailoring the nonlinear phase by such nanostructures. As a result, compact and functional surfaces can be obtained for efficient light manipulation in the nonlinear regime.

## Design and fabrication of optical metasurfaces

*Deposition of thin layers for nanostructuring*

One challenging task for identifying and obtaining functional nanostructures or surfaces with the desired properties is the proper design and fabrication. Our group uses extensive collaborations with other project partners as well as commercially available software tools for the design of the nanostructures. By combining various aspects of the properties of light like polarization, wavelength, and spatial distribution, novel multiplexing schemes can be obtained to increase the information capacity for store data for example in holograms or increase complexity in functionality. For the fabrication of the designed structures, the cleanroom facility of the CeOPP provides the required equipment. Most meta-structures are fabricated by electron beam lithography and chemical etching techniques. Here, high precision and low fabrication tolerances are important to obtain high-quality samples with the desired properties.






## Equipment & Methods

- Time-resolved optical spectroscopy
- Photon-correlation spectroscopy
- Phase and polarization sensitive spectroscopy (VIS-NIR)
- fs-nonlinear spectrocopy
- Transmission spectroscopy for UV, VIS, and NIR
- Hologram design with Gerchberg-Saxton algorithm
- Coherent Chameleon NIR-OPO
- Coherent Opera-F VIS-NIR OPA
- Coherent Monaco
- Coherent Chameleon Ultra II
- Fianium Whitelase Supercontinuum
- 10 MHz Log-in amplifier
- Cooled-CCD spectrometer for VIS/NIR
- VIS and NIR cameras
- VIS and NIR spatial light modulators
- Bruker FTIR spectrometer
- Geko autocorrelator
- Inverted optical microscope (Nikon)

# Nanostructure Optoelectronics
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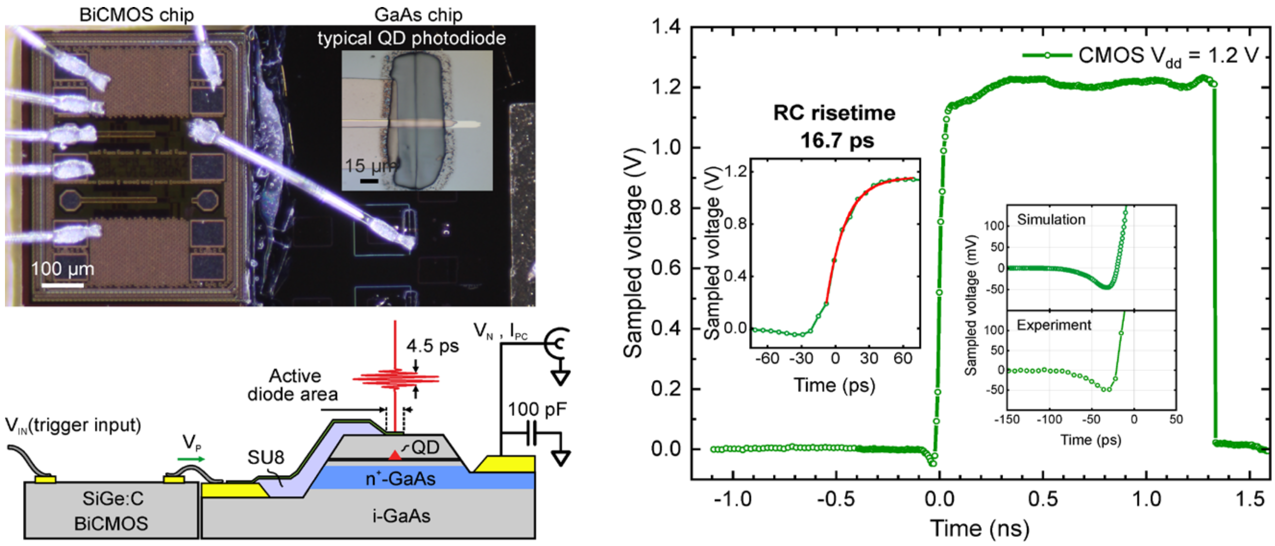
The research activities of the nanostructure optoelectronics group are focused on the physics and technology of semiconductor quantum dots and on advanced optical analytics.

Our research on quantum dots is concentrated on the investigation of single quantum systems and 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. Our work is focused on the ultrafast electric control of quantum dots in the coherent regime and on the nonlinear quantum optical control of optical transitions in quantum dots.

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.

## Ultrafast optoelectronic sampling with single quantum dots

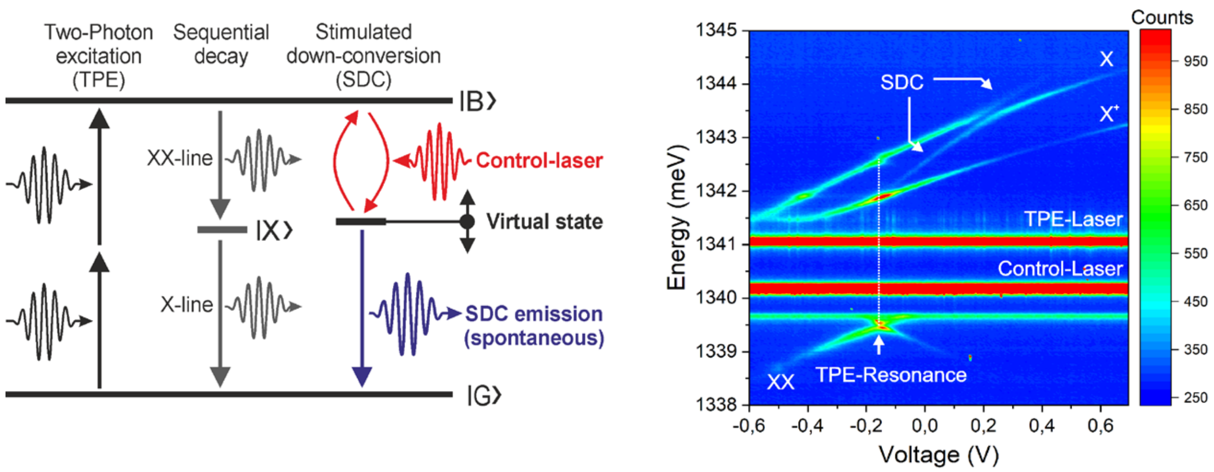
In single quantum dot photodiodes, the energy of the ground state transition can be precisely tuned via the Stark effect. Using resonant ps laser excitation and the bias-dependence of the obtained population in a quantum dot, we have been able to demonstrate optoelectronic sampling of ultrafast electric pulses with a resolution in the mV range. To achieve this, we have realized low capacitance photodiodes, which are connected to ultrafast BiCMOS circuits and operated at low temperatures. A laser-synchronous electric pulse with variable delay is used as transient bias voltage supplied at the front contact of the photodiode, acting as input of the sampling device. For each set delay, the exciton energy is tuned to resonance with the ps laser excitation by adjusting the bias on the back contact, monitored by photocurrent detection. Using this concept, we have been able to demonstrate precise optoelectronic sampling with a time resolution below 20 ps.




*Photograph and schematic view of an integrated BiCMOS chip and low capacitance quantum dot photodiode. The ultrafast output signal of the chip is sampled by a single quantum dot using synchronous ps laser techniques (From Appl. Phys. Lett. 119, 181109 (2021)).*

## Nonlinear down-conversion in a single quantum dot

In the field of quantum dot optics, the exploitation of nonlinear processes remained so far limited to the coherent control of population and to the resonant 2-photon excitation of biexcitons. With our current work we have pioneered a new concept, which enables the control of single photon emission by a nonlinear down-conversion process. Starting from a biexciton state IB>,

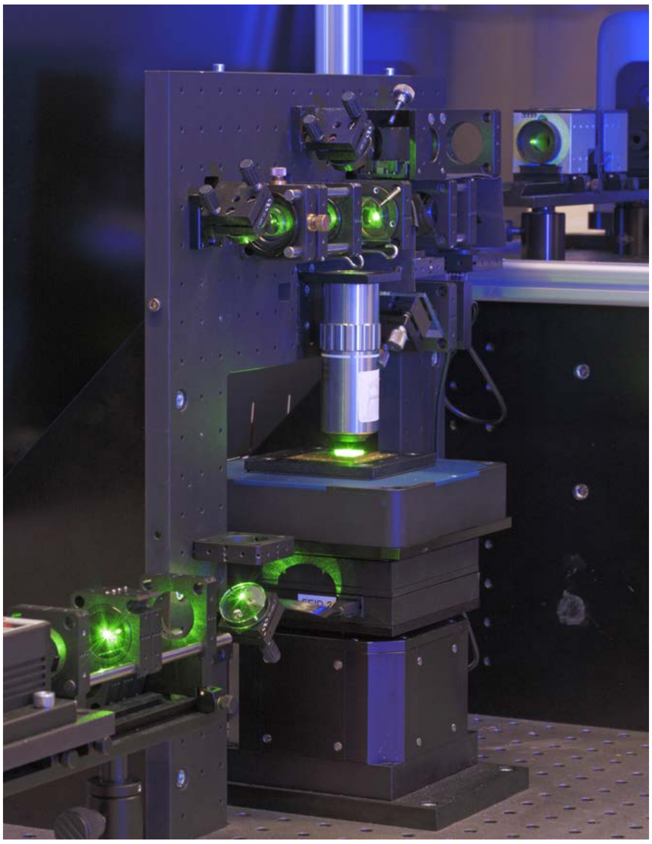



*Stimulated down-conversion (SDC) scheme for tunable single photon emission from a quantum dot. In the experiment, the SDC emission can be unambiguously identified by its characteristic Stark shift behavior, which is twice as large as compared to the X- and XX-lines (from arXiv:2105.12393 [quant-ph]).*

a tunable control laser field defines a virtual state in a stimulated process (SDC). From there, spontaneous emission to the ground state IG> leads to optically controlled single photon emission. Based on this concept, the energy and polarization of the single photon emission can be controlled in a complementary way by a classical laser field. The results lay the foundations for a new generation of nonlinear optical devices based on quantum optical principles.

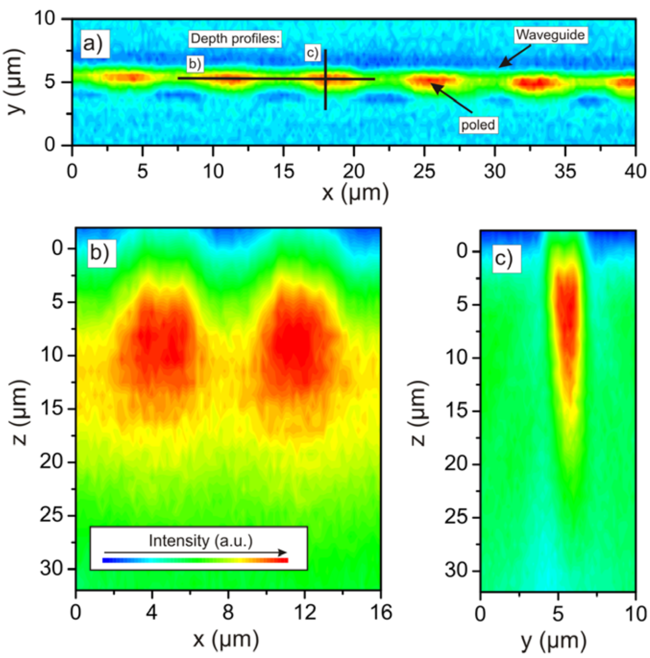
## Nonlinear microscopy and Raman imaging

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.



*Confocal Raman microscopy (UPB, Groppe)*

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 analyze defects and impurities in integrated optical circuits for quantum-optical applications.




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

## Equipment & Methods

- Spatially resolved low temperature spectroscopy
- Ultrasensitive photocurrent spectroscopy
- Coherent optoelectronics
- Low temperature electronics
- Raman spectroscopy and imaging
- fs nonlinear microscopy
- cw/ps/fs laser sources
- Optical lithography, spin coating, evaporation

# Facilities

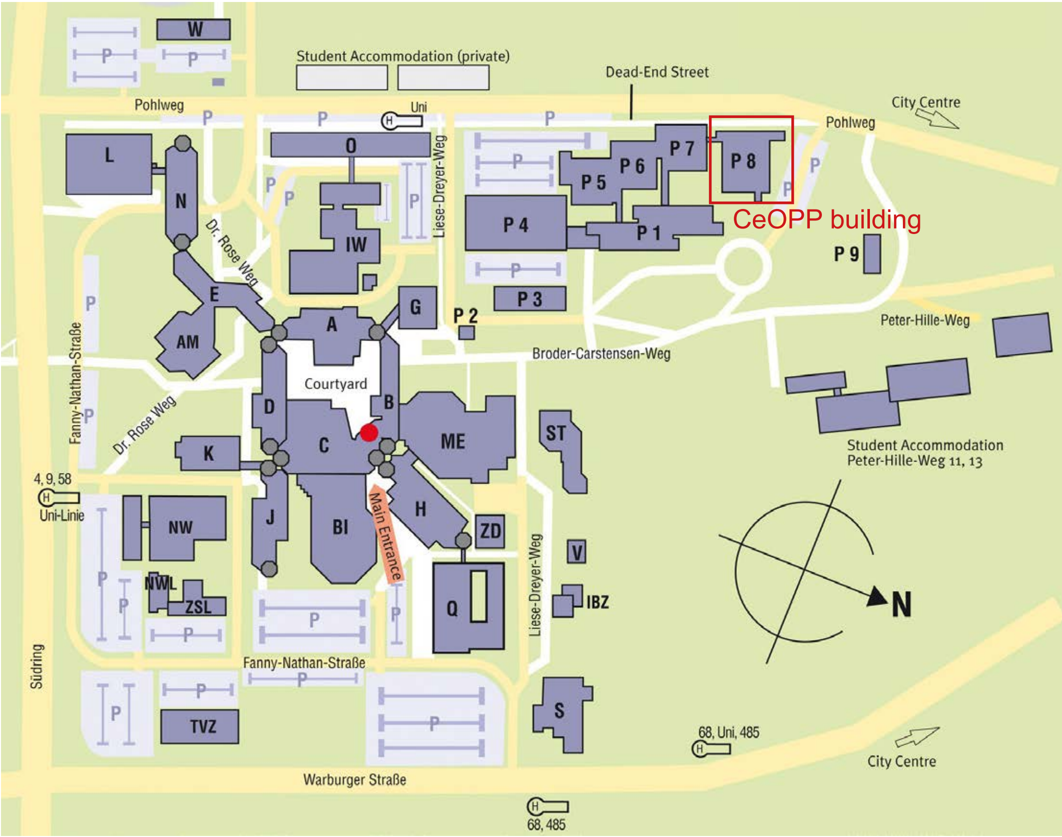
## CeOPP Building

- 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



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Student Accommodation (private)
Dead-End Street
Pohlweg
Uni
City Centre
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P 7
P 8
P 6
P 5
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P 4
P 1
CeOPP building
Liese-Dreyer-Weg
Dr. Rose Weg
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Broder-Carstensen-Weg
Peter-Hille-Weg
Courtyard
Fanny-Nathan-Straße
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Dr. Rose Weg
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Student Accommodation
Peter-Hille-Weg 11, 13
4, 9, 58
Uni-Linie
J
BI
Main Entrance
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NW
ZD
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NWL
ZSL
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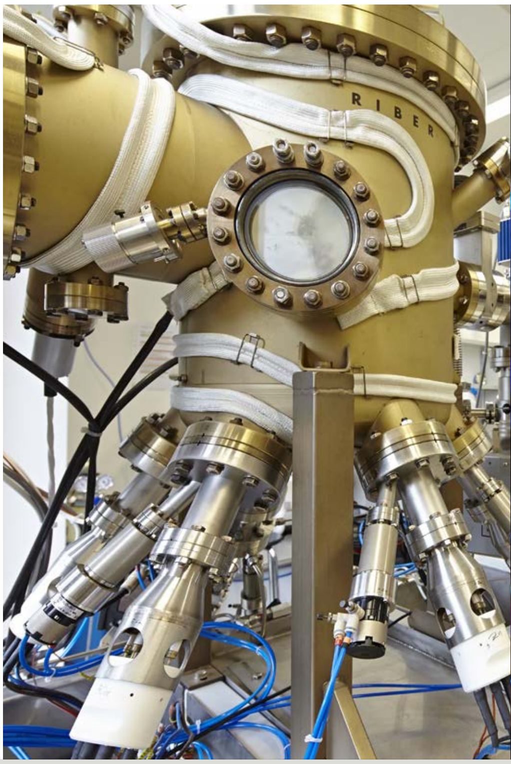
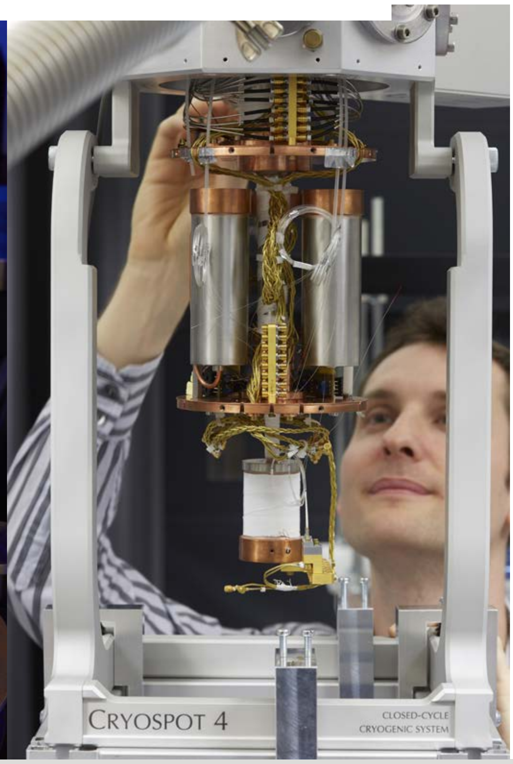
IBZ
Südring
Fanny-Nathan-Straße
S
TVZ
68, Uni, 485
City Centre
Warburger Straße
68, 485


Münster
Bielefeld
Detmold
Fürstenallee
F
ZM1
Zukunftsmeile
Neuhäuser Straße
Fürstenweg
Detmolder Straße
Ostring
Heinz-Nixdorf-Ring
Rathenaustraße
Berliner Ring
Paderborn
Centre
Driburger Straße
To the A2
Ludwigsfelder Ring
Warburger Straße
Bahnhofstraße
Exit "Paderborn Zentrum"
Main Train Station
Borchener Straße
Husener Straße
Pohlweg
Campus
Höxter
Exit "Universität"
A33
B 64
Südring
Pohlweg
Sport
B 68
Technology Park
B 64
Exit "Universität"
University GolfClub
Kassel
To the A44



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