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Preface

The scientists and students of the Walter Schottky Institute are pleased to present to you their annual report for the year 2012, summarizing the research and teaching activities which have kept us busy in the last year. This report comes a little bit later than in previous years because of some unexpected events, but we hope that you will find it still interesting and informative.

2012 has been a year of transition. One main task was to find a successor for the Chair of Gerhard Abstreiter, which took much longer than expected, but finally has come to a positive end with the appointment of Jonathan Finley in early 2013. I myself was very happy to be relieved of the duty as Dean of the Physics Department and to be able to devote again more time for research. Jose Garrido thought a while about following a call to a Professor position in Singapore, but could be convinced that Bavaria in general and Garching in particular is a much better place to live and work, so that finally he decided to stay and to take on a permanent position.

Also, 2012 has been a very productive year concerning the scientific research performed at the Walter Schottky Institute. An all-time record number of 25 PhD students have graduated in the last year. In addition, almost 70 Bachelor, Master and Diploma Theses were carried out and successfully completed in the various research groups of the Institute. The results of this work have been published in more than 100 ISI-listed publications, and the high international visibility of the Institute is documented by almost 4000 citations in 2012.

Of course one of the most important assets of our Institute are the many talented and dedicated young undergraduate and graduate students who come to us first as student helpers and eventually continue on as Bachelor, Master or even PhD students. It is a particular pleasure to be able to recognize their important contribution to the scientific work of the Walter Schottky Institute via the annual WSI Award for Diploma and Master Students endowed by the Walter Schottky Institute Association. It is therefore my privilege to congratulate Jörg Senf, Willi Aigner, Peter Wiecha and Christoph Karnetzky for having been awarded this prize in the year 2012! Of course special thanks also go to all members of the WSI Association who have made this possible by their generous donations!

Finally, I would like to use this occasion to personally thank all sponsors, friends, alumni, members and students of the Walter Schottky Institute for their continued support and contributions! It has been a real pleasure to work and be in contact with you in the past year, and I look very much forward to the upcoming celebration of our 25th anniversary in 2013!

Yours truly,

Martin Stutzmann

July 2013
Our PhDs in 2012

Roland Dietmüller

Florian Klotz

Markus Dankerl

Felix Höhne
Thomas Zabel

Simon Hertenberger

Norman Hauke
Thomas Eißfeller
Tobias Antesberger
Olaf Weidemann
Carola Oberhüttinger
Thomas Wassner

Peter Greck

Christoph Schindler
1. The Walter Schottky Institut

Brief History

The Walter Schottky Institut (WSI) is a Central Institute of Technische Universität München (TUM). It was founded in order to strengthen the interaction between basic physics and semiconductor electronics research and development. After the decision was made to create such an interdisciplinary research institute in early 1986 it took about two years until the new laboratories became operational in May 1988. This exceptionally short time for planning and construction of a modern institute building was made possible by the excellent cooperation between the Siemens AG, the Bavarian ministries, and TUM.

To accommodate the strong growth of the WSI between 2000 and 2010 in terms of projects, students, and independent research groups, an additional building was inaugurated on July 19, 2010. This new “Center for Nanotechnology and Nanomaterials” (Zentrum für Nanotechnologie und Nanomaterialien, ZNN) offers state-of-the-art laboratories and an additional clean room for all aspects of nanofabrication, nanoelectronics, nanophotonics, and biomolecular nanotechnology. Funding for this new building was provided jointly by the German Federal Government and the State of Bavaria. Many laboratories of the ZNN are operated as shared facilities in the context of the Center of Excellence “Nanosystems Initiative Munich (NIM)”.

Resources

The WSI and ZNN buildings contain laboratories and offices with a total area of about 4500 m². Both are well equipped with state-of-the-art facilities for semiconductor preparation and processing, characterization, device technology, and nanotechnology. The main resources are listed in the following:

Materials preparation and semiconductor technology

- Epitaxy systems for GaAs, InP, GaSb, GaN/AlGaN, ZnO/ZnMgO, and SiGe based heterostructures (MBE, plasma-assisted MBE, MOVPE)
- Ultrahigh purity GaAs MBE machine (electron mobilities > 10 Mio cm²/Vs)
- UHV evaporation equipment for SiGe
- Deposition systems for organic semiconductors and graphene
- Pulsed laser processing
- Laboratories for surface modification / biofunctionalization
- 250 m² class 100 (WSI) plus 150 m² class 100 (ZNN) clean room facilities with photolithography, e-beam lithography, focused ion beam processing, reactive ion etching, metallization
- S2 laboratories for bioelectronics and cell lines

Characterization and spectroscopy tools

- High resolution X-ray diffraction
- Atomic force microscopy
Transmission electron microscopy
- Electron microscopy and EDX equipment
- Photoluminescence and Raman spectroscopy (from IR to UV)
- DLTS, Optical DLTS, CV-profiling
- FTIR spectroscopy
- X-ray photoelectron spectroscopy
- High frequency parameter analyzers
- Electron spin resonance (ODMR, EDMR, pulsed EPR)
- Low temperature high magnetic field setups for magneto-transport and magneto-optics
- Special characterization facilities for laser diodes
- Electrochemical characterization facilities (cyclic voltammetry, impedance spectroscopy, patch clamp setups)

**Computational facilities**
- High end workstations

**Research groups**

The number of researchers at the Walter Schottky Institut has grown continuously. Today it accommodates the research groups headed by Gerhard Abstreiter, Markus-Christian Amann, Martin S. Brandt, Hendrik Dietz, Jonathan J. Finley, José Antonio Garrido, Alexander Holleitner, Gregor Koblmüller, Ulrich Rant, Friedrich Simmel, Martin Stutzmann, and Peter Vogl, with a total headcount of about 160, including junior research group leaders, scientific and technical staff, postdocs and visiting researchers, secretaries, and doctorate as well as diploma, master, and bachelor students. Out of these, about 30 positions are funded by TUM, while basically all the doctorate positions are financed via research projects with external funding.

The main research interests are:

- Fabrication and characterization of new semiconductor materials, material combinations, as well as functionalisation of semiconductor surfaces
- Development of novel methods for fabrication and characterization of nanostructures
- Basic physics with emphasis on electronic and optical properties of low dimensional systems
- Realisation of new semiconductor devices for applications in ultrafast electronics, optoelectronics, and as biological / chemical sensors
- Theory and simulation of modern semiconductor materials and devices
Experimental Semiconductor Physics I (Gerhard Abstreiter, Jonathan J. Finley, Alexander Holleitner, Gregor Koblmüller, Ulrich Rant):

Research projects of these groups deal with various aspects of electronic, optical, and optoelectronic properties of low-dimensional, mesoscopic semiconductor structures, the heteroepitaxy of group IV and III-V semiconductors, the development of novel methods for lateral patterning and self-assembly of quantum dots and nanowires, the use of various analytical tools for the characterization of nanometer-sized structures in collaboration with external groups, as well as the fabrication and test of new, unconventional electronic, optical and ultrafast optoelectronic devices. Examples for basic research are optical spectroscopy of single and coupled quantum dots as well as nanowires, cleaved edge overgrowth on GaAs, electronic transport, magneto-transport and tunneling in nanowires and high mobility two-dimensional electron systems, exciton-based low-dimensional circuits, and optoelectronics on the basis of single molecules as well as nanolasers. Device and technology oriented work aims at novel concepts for charge and spin storage in quantum dots, coherent devices based on quantum dots for future quantum information technology, photonic crystal micro- and nanocavities for efficient single photon sources as well as photodetectors, photovoltaics and thermoelectrics based on semiconductor nanowires. Another area of research is the test and development of nanostructures for chemical/ biological sensors using DNA based switch-sense technology and functionalized nanopores.

Semiconductor Technology (Markus-Christian Amann):

The research activities in this group are concentrated on modern technologies for III-V compound semiconductors and their use for developing advanced electronic and optoelectronic devices. This comprises the development of epitaxial, patterning, microstructuring, etching and coating techniques as well as the design and fabrication of semiconductor laser diodes and other photonic components. The applied material systems are GaAs-AlGaAs, InGaAsP-InP and antimonite based compounds that are grown with molecular beam epitaxy (MBE) and Metal Organic Vapor Phase Epitaxy (MOVPE) with an accuracy in the nanometer regime. Device structuring in the 100-nm-range is obtained by using electron-beam lithography. Reactive ion etching enables the well-defined processing of the various devices with a high material selectivity of the etching rate. The group is also well equipped with evaporation and sputtering techniques for passivation and contacting of the devices. Among the key devices are single-mode and wavelength-tunable laser diodes for the wavelength range between 1300 and 2300 nm using lattice-matched and other photonic components. The applied material systems are GaAs-AlGaAs, InGaAsP-InP and antimonite based compounds that are grown with molecular beam epitaxy (MBE) and Metal Organic Vapor Phase Epitaxy (MOVPE) with an accuracy in the nanometer regime. Device structuring in the 100-nm-range is obtained by using electron-beam lithography. Reactive ion etching enables the well-defined processing of the various devices with a high material selectivity of the etching rate. The group is also well equipped with evaporation and sputtering techniques for passivation and contacting of the devices. Among the key devices are single-mode and wavelength-tunable laser diodes for the wavelength range between 1300 and 2300 nm using lattice-matched and strained InGaAs layers on InP substrates, and InGaAs- and GaInAlAsSb-based vertical cavity surface-emitting laser diodes (VCSELs) in the 1300-2600 nm wavelength range. Our work also covers the development of injectorless quantum cascade lasers in the range of 5 to 15 µm for gas sensing. Recently quantum well-based giant optical nonlinearities were integrated into single or dual wavelength quantum cascade lasers to access the near-infrared (2-4µm) or the far infrared and Terahertz regime by intracavity sum or difference frequency generation, respectively.
The work of this semiconductor physics group deals with various aspects of new and nonconventional semiconductor materials and material combinations:

- semiconductors with a wide bandgap (GaN, InGaN, AlGaN, diamond, SiC, ZnMgO),
- disordered semiconductors (amorphous, nanocrystalline, and polycrystalline),
- advanced thin film systems (thin film solar cells, organic/inorganic heterosystems, graphene, biofunctionalized semiconductors, semimagnetic semiconductors)

Most of these material systems are prepared by suitable deposition techniques (MBE, plasma-enhanced CVD, e-beam evaporation, sputtering). Their efficient optimization is based on the large pool of structural, optical, and electrical characterization techniques available in our institute. Complementary to the usual spectroscopic techniques we have developed and employ a variety of highly sensitive methods which enable us to study the influence of defects on the electronic performance of materials and devices. Such techniques include subgap absorption spectroscopy, optically induced capacitance spectroscopy and, in particular, modern spin resonance techniques which are applied to various materials systems and devices for spintronics.

In addition to the preparation and characterization of new semiconductor materials we also work on the modification and processing of semiconductors with pulsed high power laser systems (laser crystallization, holographic nanostructuring, laser-induced etching and sintering) and investigate the potential of new material systems for novel device structures. Recent research activities have focused on nanostructured and hybrid solar cells, low thermal budget polycrystalline silicon films, printable electronics based on Si nanoparticles, AlGaN/diamond heterostructures and phosphorus spin qubits for quantum computation, III-nitride nanowires, semiconductor electrochemistry and catalysis, as well as sensors and biosensors based on GaN, diamond, and graphene.

Theoretical Semiconductor Physics (Peter Vogl):

The activity of this group focuses on the theoretical study of structural, electronic and optical properties of semiconductors. The work deals with mesoscopic structures, new materials, and novel devices, in the attempt to understand their basic physics and to predict their behavior. The research conducted in the group aims at the development of theoretical tools which can support present experimental activities and propose new ideas and solutions for the future, as indicated by the strong interaction with industrial laboratories and with engineering university departments. Sophisticated quantum mechanical calculations are used for determining the electronic structures and the optical properties of a variety of semiconductor materials and systems. The information from such fundamental studies constitutes the basis for the analysis of the transport properties of such materials and for the development of reliable numerical tools for device modeling. Recent activities in this group include ab-initio studies of spin devices, prediction of nov-
el magnetic field effects, development of multiscale methods for film growth, and the design and modeling of semiconductor based quantum information devices.

The research activity of the institute thus covers a wide spectrum from basic physics in low-dimensional semiconductor structures to the development of novel or improved electronic, optoelectronic and sensor devices based on semiconductor hetero- and nanostructures. The close collaboration between the different groups and the availability of various experimental techniques are the essential basis for the successful development of novel semiconductor devices. Close contacts with industrial partners have also proven to be very fruitful and stimulating in developing new ideas and in following new directions which may be relevant for future applications.

**Biomolecular Nanotechnology (Hendrik Dietz):**

Inspired by the rich functionalities of natural macromolecular assemblies such as enzymes, molecular motors, and viruses, we seek means for building artificial nanodevices that can execute user-defined tasks. Molecular self-assembly with nucleic acid offers an attractive route to achieve this goal and allows for building nanodevices that open new paths to scientific discovery in biomolecular physics and protein science. The group studies biomolecular self-assembly phenomena and invests significant effort in characterizing the fundamental interactions that stabilize biomolecular complexes. Transmission electron microscopy, electrophoresis, and single molecule methods such as optical trapping and fluorescence microscopy are among the routine analysis tools.

**Biomolecular Systems and Bionanotechnology (Friedrich Simmel):**

The Biomolecular Systems group explores the physical properties of natural and artificial biomolecular systems and their applications in bionanotechnology. The long term goal of its research is the realization of self-organizing molecular systems that are able to respond to their environment, compute, move, reconfigure, or evolve.

More specifically, the group’s current main research directions comprise:

- biophysics of nucleic acid-based molecular structures and devices,
- DNA self-assembly (DNA origami),
- synthetic in vitro biochemical circuits/cell-free systems,
- in vivo synthetic biology with bacteria.

The group mainly works with nucleic acid molecules (from small aptamers to full genes) as they are uniquely suited for the construction of synthetic biomolecular systems – they can act as “programmable” molecular building blocks, but also as switchable molecular structures, or as information carriers and processors. The group utilizes are wide variety of experimental techniques ranging from basic biochemical methods over fluorescence spectroscopy and microscopy, microfluidics and single cell studies to single molecule techniques such as super-resolution microscopy, nanopore force spectroscopy and AFM.
Apart from the extensive research activities all groups are involved in teaching within their respective departments. Besides the usual teaching responsibilities in undergraduate and graduate courses, special emphasis is put on the education of diploma and doctoral students in the physics and technology of present and future nano-devices and of low dimensional semiconductor structures.
Fundamental Semiconductor Physics
Coherent optical control of single spin qubits in single self-assembled artificial atoms and molecules

K. Müller¹, P. Ardelt, A. Bechtold, R. Ripszam, T. Kaldewey, M. Bichler, G. Koblmüller, G. Abstreiter, and J.J. Finley

The ability to control and exploit quantum coherence and entanglement drives research across many fields ranging from ultra-cold quantum gases to spin systems in condensed matter. A key requirement for exploiting spins as qubits is the ability to initialize, control and read-out single spin states.

Recently, we employed ultrafast photocurrent spectroscopy to probe charge [1-2] and spin [3] dynamics of individual quantum dot nanostructures as well as coherently control single spin states [4]. We reported how a precisely timed sequence of three monochromatic ultrafast (~2-5 ps) optical pulses with a well-defined polarization can be used to (i) prepare an arbitrary superposition of exciton spin states in an individual InGaAs quantum dot photo-diode, (ii) arbitrarily control the spin-wavefunction without an applied magnetic field and (iii) read-out with high fidelity the quantum state in an arbitrary basis simply by detecting a strong (~2-10 pA) electric current flowing in an external circuit [3]. The results obtained show that the combined preparation, control and read-out of the spin quantum state can all be performed with a near-unity (>97%) fidelity.

Due to the finestructure splitting of self-assembled quantum dots, the neutral exciton forms a spin qubit with two energy eigenstates that can be addressed using the linear optical polarizations H and V (inset figure 1). Therefore, arbitrary superposition spin states can be initialized by directly mapping the polarization of a resonant ps-duration laser pulse to the exciton spin Bloch sphere. In pump-probe spectroscopy experiments this exciton spin can be read out by either the spin selectivity of the conditional absorption of the biexciton transition (2X) or the spin-selectivity of the stimulated emission (X). As an example we present in figure 1(a) pump-probe spectra for pumping the exciton with R polarized light and probing the spin state with R and L polarizations and in (b) the temporal evolution of the peaks. Clearly, the spin selectivity of the conditional absorption of 2X and stimulated emission of X can be seen in (a) and fully modulated antiphased oscillations resulting

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from the spin precession in (b). We reported the arbitrary initialization of an exciton spin and the projection readout along arbitrary axis.

Arbitrary, high fidelity coherent optical control is achieved by applying an additional $2\pi$-pulse with a precisely defined polarization in resonance with X between initialization and readout. This control pulse does not affect the population of the X state but induces precise rotations of the exciton spin state. The rotation angle is directly given by the angles $\Phi'$ and $\Theta'$ between the position of the spin state on the Bloch sphere and the polarization of the control pulse (figure 2a). Typical results are presented in figure 2 that shows spectra for a variation of the angle $\Phi'$ in (b) and $\Theta'$ in (c). Clearly, in (b) the amplitude of the oscillations stays constant and the phase changes while in (c) the phase stays constant and the amplitude changes. Both figures together demonstrate arbitrary coherent control of the exciton spin state using a single resonant ps-duration laser pulse. Thereby, the fidelity of the control is again near unity, limited to >97% by the ~100fA readout noise in the photocurrent signal.

Our methods are fully applicable to other optically addressable quantum emitters and have strong potential for scaling to more complex systems such as molecules, color centers, dopant bound excitons or valley polarization in 2D-transition metal chalcogenides.

![Figure 2](image)

**Fig. 2:** Fully resonant coherent optical control for control and readout pulses tuned to cgs-X. The control angles are varied in (b) over the range $\Phi' = 0$-$\pi$, $\Theta' = 0$ and in (c) from $\Phi' = 0$, $\Theta' = 0$-$\pi$.

Local photocurrent generation in thin films of the topological insulator Bi$_2$Se$_3$

C. Kastl, T. Guan$^1$, X. Y. He$^1$, K. H. Wu$^1$, Y. Q. Li$^1$, A. W. Holleitner$^*$

In recent years, a class of solid state materials, called topological insulators, has emerged\cite{1}. In the bulk, a topological insulator behaves like an ordinary insulator exhibiting states with a band gap between valence and conduction band. At the surface, gapless states exist showing remarkable properties such as helical Dirac dispersion near zero energy and suppression of backscattering. Initially, the existence of such states was predicted theoretically and verified experimentally for two-dimensional HgTe/Hg quantum wells \cite{1}, \cite{2}. Later on, also three-dimensional topological insulators, such as Bi$_2$Se$_3$, found \cite{3}, \cite{4}.

In the three-dimensional systems, the characterization of the surface states via transport experiments is often hindered by a large residual bulk charge carrier density. However, both theoretical and experimental works provide evidence that the helical surface states can be selectively addressed by excitation with circularly polarized light and subsequently read out in a corresponding photocurrent measurement \cite{5}, \cite{6}.

Here, we experimentally investigate photocurrents generated in thin films of Bi$_2$Se$_3$ grown by molecular beam epitaxy \cite{7}. By measuring the photocurrent at zero bias voltage, we find a global photoresponse of the overall circuit, whose average magnitude depends only on the device geometry and excitation intensity. Remarkably, the photocurrent shows reproducible submicron fluctuations with positive and negative amplitudes. By changing the charge carrier density via a back gate, these spatial photocurrent patterns can be continuously deformed. Therefore, we conclude that the photocurrent is generated by local fluctuations of the potential landscape in Bi$_2$Se$_3$. Our findings are consistent with a photoresponse predicted very recently for gapless materials \cite{8}, and they may prove useful for the design of photodetectors based on topological insulators. Furthermore, such information on fluctuations may be valuable for understanding electron transport properties such as linear magnetoresistance as well as for the study of the exotic physics near the Dirac point in topological insulators.

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Fig. 1: (a) Reflectance map of a 10 nm thin film of Bi$_2$Se$_3$ (bright) on a SrTiO$_3$ substrate (dark). Photocurrent $I_{\text{photo}}$ is measured between two unbiased contacts A and B as a function of excitation position. (b) Photocurrent map of same area as in (a) ($f_{\text{chop}} = 239$ Hz; $I_{\text{opt}} = 1.2$ kW/cm$^2$). (c) Photocurrent map of the area marked by dotted rectangle. Dotted lines indicate boundary of channel ($f_{\text{chop}} = 239$ Hz; $I_{\text{opt}} = 0.9$ kW/cm$^2$).


Supported by the DFG via SPP 1285 (grant HO 3324/4)
Tunable emission from excitonic traps and antitraps

Katarzyna Kowalik-Seidl, Xaver P. Vögele, Georg J. Schinner, Jens Repp, M.P. Stallhofer, Dieter Schuh, Werner Wegscheider, Jörg P. Kotthaus, and Alexander W. Holleitner

Traps for dipolar excitons, generated in semiconductor double quantum wells, are subject of current research on both a fundamental level and for potential electro-optic applications. The widely tunable recombination lifetime of such excitons enables the formation of excitonic ensembles with varying density. Therefore, these excitons are ideal composite particles for studies of dipole induced many-body interactions. Different methods to spatially confine dipolar excitons have been realized, either by using aleatory traps created at the quantum wells’ interfaces or by building stress-induced, magnetic, and electrostatic traps [1,2,3]. In comparison, electrostatic traps are highly advantageous because of their facile tunability. Gated structures for controlling dipolar excitons are also investigated for their potential applications in electro-optic devices, and so far it has been demonstrated: i) the controlled storage of excitons (photonic memories), ii) spin memory coded in the exciton polarization [4], and iii) basic logical operations with micrometer size exciton circuits. For realizing such devices on a submicron or even nanoscale dimension, lateral electric fields between two adjacent gates need to be considered. Hereby, lateral escape dynamics of photogenerated charge-carriers become important, and typically, it is assumed that these hinder the functioning of effective exciton traps and devices.

Fig. 1: Sketch of a trapping/antitrapping device for dipolar excitons. (a) Yellow: central gate C-gate with the surrounding guard gate G-gate. The voltages $V_C$ and $V_G$ are applied with respect to the back gate (blue). The dipolar excitons are excited in the double quantum well (red). (b) Fitted energy of the indirect exciton photoluminescence vs. voltage $V_C$ for the transition of a trap to an antitrap configuration. Different colors correspond to different G-gate voltages $V_G$. Vertical dashed lines mark the configuration $V_C = V_G$ for each measurement series [5].

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3 Institut für Experimentelle und Angewandte Physik, Universität Regensburg, Regensburg.
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We demonstrate that such charge-carrier dynamics can be tailored in a way that the overall photon emission of an excitonic trapping potential is efficiently enhanced \[5\]. We present photoluminescence emission studies of dipolar excitons from both an electrostatically defined trapping and antitrapping potential. The excitonic emission is surprisingly enhanced for the excitonic antitrap compared to the trap configuration. The reason for this counterintuitive behavior is a competition of processes determining the eventual excitonic photon emission. These are the exciton formation, the dipole-dipole interaction between the excitons, and the lateral escape dynamics of both electrons and holes in the trapping and antitrapping potentials \[5\].


Supported by the Deutsche Forschungsgemeinschaft DFG via project KO 416/17 and the excellence cluster “Nanosystems Initiative Munich” (NIM).
Photoconductance of gold nanoparticles in the Coulomb blockade regime

Markus Mangold, Michel Calame¹, Marcel Mayor², and Alexander W. Holleitner*

Arrays of metal nanoparticles in an organic matrix have attracted a lot of interest due to their diverse electronic properties. By varying parameters such as the nanoparticle material, the matrix material, the nanoparticle size, and the interparticle distance, the electronic behavior of the nanoparticle array can be substantially tuned and controlled. For strong tunnel coupling between adjacent nanoparticles, the assembly exhibits conductance properties similar to the bulk properties of the nanoparticle material. For instance, assemblies from conducting nanoparticles show an Ohmic transport behavior, while superconductivity is observed in assemblies from strongly coupled superconducting nanoparticles [1]. When the coupling between the nanoparticles is reduced, a metal-insulator transition is observed in the overall assembly. In insulating nanoparticle arrays where the individual particles are only weakly coupled to neighboring particles, the single electron charging energy $E_c$ of a nanoparticle can govern the electron transport [2,3]. The transport through the array is blocked, unless an energy of $E_c$ is provided to the electrons by thermal activation or an applied bias. This is the so-called Coulomb blockade. Arrays in the Coulomb blockade regime are interesting for electronic applications due to their highly nonlinear current-voltage characteristics.

Fig. 1: (a) Photocurrent $I_{\text{photo}}$ of a 2D nanoparticle array as a function of $V_{sd}$ measured at $T = 13.7\,\text{K}$ (black) and $T = 25\,\text{K}$ (blue) ($E_{\text{photon}} = 2.07\,\text{eV}$, $I_{\text{opt}} = 0.7\,\text{kW/cm}^2$ and $f_{\text{chop}} = 1605\,\text{Hz}$). (b) Sketch of a nanoparticle array at bath temperature $T_0$ on a SiO$_2$ substrate contacted by gold electrodes and irradiated by a focused laser beam increasing the local temperature to $T_1$. Second and third panel represent the potential $U$ and the electric field $E$ as a function of position in the irradiated (solid line) and the non-irradiated (dashed line) array. (c) Calculated photocurrent $I_{\text{calc}}$ as a function of $V_{sd}$ for $T_0 = 13.7\,\text{K}$, $T_1 = 16.2\,\text{K}$ (black) and $T_0 = 25\,\text{K}$, $T_1 = 26.6\,\text{K}$ (blue). (d) Calculated absorption $A_{\text{eff}}$ of a nanoparticle array as a function of the photon energy $E_{\text{photon}}$.

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We report on the investigation of the photoconductance of gold nanoparticle arrays in the Coulomb blockade regime. At room temperature, the photoconductance of gold nanoparticle arrays can be dominated by bolometric conductance enhancement [4], plasmonic field enhancement [5], a trap state filling in the nanoparticle cores [6], and the resonant excitation of molecules incorporated into the arrays [7]. In the Coulomb blockade regime, we demonstrate that the photoconductance is governed by a redistribution of the potential landscape in the nanoparticle array (Figure 1(a), (b), (c) and [8]). We optically excite the nanoparticle array with a focused laser beam. Due to absorption of the incident light [Figure 1(e)], we locally heat up the nanoparticle array [4]. The inhomogeneous temperature profile leads to a redistribution of the potential landscape and, by this, to a strong field enhancement in the rest of the array [Figure 1(b)]. Our interpretation is substantiated by the results of a two-beam photoconductance investigation. We use two individually controllable laser beams for the local optical excitation of the array. In such a scheme, we can influence the electric field at the position of beam I by the use of beam II. In the case of the two-beam excitation, we observe a negative differential photoconductance across the nanoparticle array. The occurrence of a negative differential photoconductance is fully consistent with our model of an inhomogeneous temperature profile and the redistribution of the potential landscape in the nanoparticle array [8].

Our results show that gold nanoparticle arrays in the Coulomb blockade regime are very sensitive to a local lift of the Coulomb blockade. Therefore, we can obtain local control of the electric transport in a nanoparticle array by optical means. This can be interesting for applications as optical sensors or for local temperature measurements [8].

Enlarged magnetic focusing radius of photoinduced ballistic currents

Markus Stallhofer, Christoph Kastl, Marcel Brändlein, Dieter Schuh¹, Werner Wegscheider², Jörg P. Kotthaus³, Gerhard Abstreiter, and Alexander W. Holleitner⁴

We exploit GaAs-based quantum point contacts (QPCs) to spatially resolve and analyze the ballistic, non-equilibrium flow of photogenerated electrons in mesoscopic circuits. Electron-hole pairs are photogenerated in a two-dimensional electron gas (2DEG) and the resulting current of photogenerated electrons through an adjacent QPC is measured as a function of the laser spot position [1]. We utilize this so called optical-beam-induced-current (OBIC) technique to directly analyze the flow-patterns of the photogenerated electrons in a 2DEG embedded in an AlGaAs/GaAs quantum well at a perpendicular magnetic field, as shown in Fig. 1 [2]. In contrast to magnetic focusing results gained from transport experiments, we uncover the magnetic focusing dynamics of photogenerated non-equilibrium excess electrons in a 2DEG.

We observe laterally curved trajectories with a radius being inversely proportional to $|B|$ as expected for cyclotron motion. However, for both resonant and non-resonant optical excitation of the quantum well, the radii of the measured trajectories are 10 to 30 times larger than anticipated, assuming an effective electron mass in GaAs of $m^* = 0.067 m_e$. We explain the experimental results by electron-electron scattering processes. In particular, we perform Monte Carlo simulations of the effective magnetic focusing radii of photogenerated excess electrons in a perpendicular magnetic field at the presence of small-angle scatterers.

The simulations agree very well with the data. Our findings suggest that due to an enhanced influence of electron-electron scattering, the radius of the trajectories of hot ballistic electrons is generally enlarged. Our observations underline the predominant influence of electron-electron interaction processes in mesoscopic and nanoscale optoelectronic circuits [2] and therefore photodetectors.

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Materials Science
Growth and optical properties of In-rich InGaAs nanowire arrays on Si (111) with high compositional uniformity


InGaAs nanowires (NW) exhibit significant potential to drive new applications in nanoelectronic and -photonic devices especially when integrated on low-cost silicon (Si) platform. To date, nearly all work on free-standing InGaAs NWs was conducted under catalyst-assisted methods, i.e., by Au or self-catalyzed group-III-elemental droplets. These catalytic approaches, however, pose a number of limitations: incompatibility of Au with III-V-on-Si systems, difficulties in achieving abrupt NW heterostructures and severe issues for alloying InAs with GaAs due to the underlying vapor-liquid-solid (VLS) growth mode.

Recently, we reported a completely non-catalytic, self-induced growth of InAs NWs on Si (111) by solid-source MBE [1]. In order to incorporate Ga homogeneously into InAs NWs, it is important to identify the optimum growth conditions necessary to allow formation of ternary InGaAs NWs. As a preliminary step we therefore explored first the entire growth parameter space and rate limiting mechanisms in non-catalytic InAs NWs grown by MBE. Surprisingly huge growth temperature ranges are found upon dramatic increase of V/III ratio with maximum growth temperatures close to ~600 °C, which are similar to what is commonly used for GaAs NW growth [2]. Based on quantitative in-situ line-of-sight quadrupole mass spectrometry, we determined also the rate limiting factors in this high-temperature InAs NW growth window by direct monitoring the critical desorption and thermal decomposition processes of InAs NWs. The (111)-oriented InAs NWs evidence excellent thermal stability at elevated temperatures even under negligible supersaturation [2]. The unique features of high-T growth and excellent thermal stability are key parameters to access growth temperature regimes appropriate for alloying non-catalytic InAs NWs with GaAs.

We used this knowledge to further enable the growth of high-periodicity composition-tuned InGaAs NW arrays by employing nanoimprint lithography (NIL) for large-scale pre-patterned Si (111) templates [3] (see also Fig. 1). For the In1-xGa,xAs NW arrays with Ga contents up to x ~ 0.4 uniform incorporation of the respective group-III elements (In, Ga) was achieved, as confirmed by high-resolution x-ray diffraction (HRXRD) and energy dispersive x-ray spectroscopy. Low-temperature (20K) photoluminescence per-

![Fig. 1: (a) Photograph (upper panel) and corresponding top-view FE-SEM image (lower panel) of a site-selectively grown In1-xGa,xAs NW array on NIL-SiO2/Si (111) using a (f\text{As}/f\text{Ga}) ratio = 0.1; (b-d) Close-up FE-SEM images in bird’s eye view (tilt angle 70°) of (b) the same In1-xGa,xAs NW array as viewed in (a), and In1-xGa,xAs NW arrays grown under different (f\text{As}/f\text{Ga}) ratio of 0.3 (c) and 0.5 (d).]
formed on these In-rich In$_{1-x}$Ga$_x$As NW ensembles (>10$^3$ NWs) reveal state-of-the-art linewidths of ~29–33 meV, independent of Ga content, suggesting an overall low degree of phase separation [3]. According to the composition tuning of the InGaAs NWs the low-T PL peak emission energies can be also tuned from ~0.4 – 0.7 eV (Fig. 2a). In addition, we have also grown composition-tuned InGaAs NW arrays in a self-assembled manner and found that these arrays show larger compositional inhomogeneity evidenced by increased peakwidths in 2θ-ω HRXRD scans as well as broadened Raman modes [3].

Interestingly, based on self-assembled binary InAs NWs we could also determine a characteristic blue–shift of the PL peak emission by reducing the NW diameter [4]. To account for this blue-shift we considered quantum confinement effects based on the diameter difference of NWs and calculated the respective band–edge energy shift between the ground states of the conduction band (CB) and the valence band (VB) (see also Fig. 2b). The simulated data (open symbols) shows a characteristic 1/$d^2$ relation between band-edge energy and NW diameter. The data illustrates that the onset of quantum confinement for InAs NWs occurs already at fairly large NW diameter (> 60 nm), as a result of the very small electron effective mass of InAs. The measured PL peak energies are also plotted and show good agreement with the simulated results, confirming that quantum confinement plays a major role in thin In-rich InGaAs NWs.


**Fig. 2:** (a) Normalized low-temperature (20 K) PL spectra of composition-tuned site-selective In$_{1-x}$Ga$_x$As NW arrays on NIL-SiO$_2$/Si (111). (b) Band-edge energy shift as a function of NW diameter for InAs NWs showing simulated data based on radial quantum confinement of the ground state energy (open symbols) in comparison with as-measured data from PL peak positions (closed symbols).
Optimization of high-mobility AlAs/AlGaAs quantum well heterostructures on exact and misoriented GaAs (111)B

Florian Herzog, Max Bichler, Sunanda Prabhu-Gaunkar, Wei Zhou, Matthew Grayson, and Gregor Koblmüller

Aluminum arsenide (AlAs) semiconductors have gained significant attention due to their bulk three-fold degeneracy of the X-conduction band valleys and their heavy and anisotropic conduction band effective masses, providing for large exchange effects. With near-perfect lattice-match to GaAs this multivalley semiconductor is further an excellent system for fabrication of high-mobility, modulation-doped quantum wells (QWs), where large progress was recently achieved in (001) and (110)-oriented AlAs/AlGaAs two-dimensional electron systems (2DES) with mobilities in excess of $10^5$ cm$^2$/Vs. Despite these advantages, the three-fold valley degeneracy is prone to break due to strain and quantum confinement effects in strained AlAs/AlGaAs QW heterostructures, leading to two-fold [in (001)-oriented QWs] or one-fold [in (110)-oriented QWs] valley degeneracy.

In contrast, for symmetry reasons (111)-oriented AlAs QWs should preserve the three-fold valley degree of freedom. This perfect SU(3) symmetry is expected to add an extra valley degree of freedom as compared to (001) and (110)-oriented AlAs QWs, allowing for ultimate exploration of interaction effects such as anisotropic composite Fermion mass and SU(3) valley skyrmions.

Here, we recently investigated the growth of high Al-content AlGaAs thin films and AlAs/AlGaAs QW heterostructures on both exactly- and mis-oriented GaAs (111) B substrates as a first step towards (111)-oriented AlAs QWs. In particular, we demonstrated a complementary methodology of atomic force microscopy (AFM), transmission electron microscopy (TEM) and X-ray diffraction (XRD) to quantitatively probe the presence of twin defect domains and surface mounds in the as-grown films as a function of growth parameters.

We found that unlike for GaAs, high Al-content ($x = 0.45$) AlGaAs layer grown at common temperature (650°C) on exactly oriented GaAs (111)B substrate is interspersed with deep triangular-shaped pits with facets aligned along {110} directions (Fig. 1a). These features were identified as twin defect complexes from TEM investigations (Fig. 1b). In contrast, high growth temperatures of 690°C and above resulted in a remarkable reduction of both surface pits (Fig. 1c) and related twin defect density (Fig. 1d). These observations were further corroborated by XRD measurements of the asymmetric (220) twin-related reflections.

Fig. 1: AFM surface morphologies of 350-nm thick $\text{Al}_0.45\text{Ga}_{0.55}\text{As}$ grown on exactly oriented GaAs (111) B substrate at (a) 650°C and (c) 690°C (inset: $1 \times 1 \mu\text{m}^2$ AFM image showing distinct step-terrace structure). Corresponding plan-view TEM images of the same films taken along the (111) zone axis are shown for growths at 650°C (b) and 690°C (d).

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In binary AlAs films grown at even higher temperatures on exactly oriented GaAs (111) B (720°C) pyramidal mounds and twin defects were found to be always present due to the reduced adatom mobility of Al. Enormous improvement of surface morphology and surface defect structure was achieved for AlAs growth on slightly mis-oriented GaAs (111) B substrates. Using GaAs (111) B substrates with miscut angles of 2° toward [211̅] and 2° toward [011], resulted in AlAs layers with an atomically flat step terrace structure without any trace of twin-defect related surface pits. For consecutive AlAs/AlGaAs heterostructures, growth on substrates with miscut toward [211̅] was selected.

Using optimized growth conditions for bulk Al$_{0.45}$Ga$_{0.55}$As and AlAs layers (i.e., $T = 690$ °C (AlGaAs), 720 °C (AlAs), $\text{As}_4$(BEP) = $0.8 \times 10^{-5}$ mbar) we fabricated a full modulation-doped AlAs/AlGaAs QW structure with both layer sequence and band diagram depicted in Fig. 2a. Specifically, a 15-nm wide double-sided doped AlAs QW layer is sandwiched between the Al$_{0.45}$Ga$_{0.55}$As matrix, where symmetric Si-doping layers $\delta_2$ and $\delta_3$ provide electrons to the QW while $\delta_1$ was implemented near the surface to pin the conduction band down to the Fermi level and to satisfy mid-gap surface states. This structure was grown both on exactly oriented GaAs (111) B substrates (reference) and mis-oriented substrates with 2° miscut toward [211̅]. The surface morphologies represented in Fig. 2b show large pits and trenches with overall high surface roughness for the structure grown on exactly oriented GaAs (111) B. Due to the large amount of twin defects present in the active region of this structure, electrical measurements revealed insulating behavior (room-temperature two-point resistance $> 10$ MΩ).

In contrast, smooth step-flow like morphology was preserved for the entire layer structure grown on the mis-oriented substrate (Fig. 3c), indicating high-quality growth free of twin defects. As expected, the modulation-doped AlAs QW structure conducts well at both room temperature and low temperatures as revealed from classical Hall and van-der Pauw measurements. For the selected Si doping in our structure we obtained low-temperature (1.5 K) 2DES mobilities of $\mu \sim 5000$ cm$^2$/Vs in dark at sheet carrier densities of $n^{2D} \sim 2.6 \times 10^{11}$ cm$^{-2}$ and record $\mu \sim 13200$ cm$^2$/Vs ($n^{2D} \sim 5.2 \times 10^{11}$ cm$^{-2}$) when illuminated with red light and post-illumination annealing at 30K.

Esaki tunneling performance of In(Ga)As-nanowire/Si heterojunction tunnel diodes

Tao Yang, Simon Hertenberger, Stefanie Morkötter, Gerhard Abstreiter, and Gregor Koblmüller

Compound semiconductor-based tunnel diodes have recently become very attractive for multijunction solar cells and low-power post-CMOS devices. In particular, their integration into nanoscale field effect transistors (tunnel-FET) is expected to leverage very power-efficient devices which operate at low supply voltages (sub-0.5 V), fast switching speeds and reduced subthreshold swing. In this regard, combining downscaled narrow-gap III-V materials with high interband tunneling on Si substrate is a much desired strategy for future tunnel-FET device architectures. Utilizing vertical nanowires (NW) with small diameter not only reduces the large mismatch constraints with Si, but enables a gate-all around geometry ideal for efficient gate modulation of the channel region, as well as a platform for ultra-high density integration.

Recently, we reported the fabrication and characterization of n-type In(Ga)As-NW tunnel diodes directly integrated on p-type Si substrate [1]. All In(Ga)As NWs were grown by solid-source molecular beam epitaxy (MBE) in a completely catalyst-free growth mode on SiO₂-templated Si(111) substrates [2,3], yielding epitaxial and fully relaxed, free-standing NW.

To characterize the interband tunneling properties of individual n-In(Ga)As-NW/p-Si diodes we exploited the genuine method of conductive atomic force microscopy (cAFM) (see Fig.1). This method provides the major advantage of a nanoscale probe contact to acquire current maps, i.e., current distribution over huge numbers of NW-based diodes with almost no processing, as well as in-depth information on individual NWs by voltage-dependent sweeps at room-temperature.

Current maps under forward bias reveal a bimodal distribution of NW/Si heterojunction tunnel diodes exhibiting either negative differential resistance (NDR, Esaki diode) or high excess currents (without NDR) due to misfit-related interface defects (Fig.1c and Fig.2). This is also evidenced by different heterojunction base area features in cross-

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sectional TEM micrographs. The interband tunneling features with high tunnel currents (>40 kA/cm²) were only observed on highly p-type doped Si substrate (>10¹⁹ cm⁻³), while lower substrate doping yielded a transition to normal asymmetric p-n diode behavior with large reverse bias breakdown voltages (V < -3V) (see also Fig.2). This high-field electrical breakdown attributed to interband tunneling becomes most prominent for the highest substrate doping level. In this case, the Fermi level is positioned well below the valence band (VB) of the p-Si. Thus, electrons from the VB in the p-side (Si) tunnel to the conduction band (CB) in the n-side (InAs) at low reverse bias (compare Fig. 2b).

More interestingly, we demonstrated that decreasing the InAs NW diameter from ~ 90 nm to ~25 nm leads to improved Esaki diode properties with record peak-to-valley current ratios (PVCR) close to 3 [1]. This remarkable finding evidences very abrupt p-n heterointerfaces with negligible defect densities between the two very dissimilar materials.

Instead of downscaling the radial dimensions of InAs NWs, another means to reduce excess defect densities at the NW/Si interface is to lower the lattice mismatch by using ternary InGaAs NWs. This should enable NDR characteristics with good PVCR at larger NW diameter. We showed that increasing the Ga content in In-rich ternary InGaAs NWs can preserve high PVCR (up to 2.6), while the peak current shifts to lower voltages due to reduced Fermi energy in InGaAs. All the tunneling properties were modeled and confirmed on the basis of band profile calculations.


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**Improved black silicon for photovoltaic applications**

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Nano-textured silicon, also referred to as black silicon (b-Si), is a material with an optically graded surface, which shows a reflectivity as low as 1 – 5 % in the whole range of Si absorption. Nano-texturing of thin silicon wafers and films results also in an additional enhancement of the optical absorption due to efficient light trapping. The unique optical properties of b-Si, as well as the opportunity to produce nano-textures on different silicon substrates (single- or multicrystalline wafers, amorphous or microcrystalline Si thin films) are of significant interest for photovoltaic applications.

In this work, we focus on the surface modification of b-Si nano-textures prepared by a gold-catalyzed wet etching process [1]. In order to minimize the surface area to the limits required for the favorable optical performance, we have applied an additional etching step, the standard clean 1 (SC1) from the common RCA cleaning sequence. The morphology of the as-prepared nano-texture without this additional step can be seen in Figure 1(a). It consists of cone-like hillocks, terminating in bundles of fibrous matter with characteristic dimensions well below the SEM resolution – i.e. smaller than ~ 5 nm. Photoluminescence and optical reflectivity measurements provide clear evidence that these structures can be associated with nano-porous silicon (np-Si). The np-Si envelope forms a secondary density-graded structure on top of the cone-like hillocks, which forms the primary density-graded structure desired for light trapping and reflectivity reduction. Such a two-layer morphology might be disadvantageous for applications in solar cells in many aspects: for example, the enlarged internal surface area of the np-Si can result in high surface recombination and will be difficult to passivate through the tiny pores. In contrast, the modified morphology (Figure 1(b)) obtained after SC1 treatment of the initial (as-prepared) texture is an exemplary prototype of a graded black nano-texture with minimal surface area. The small features of porous Si were preferentially etched away, while the larger features of dense Si did only slightly decrease in size. This leads to a complete removal of the np-Si envelope. As can be seen in the cross section in Figure 1(b), the resulting modified nano-texture consists of cone-like hillocks with heights of around ~ 250 nm and a base of around ~ 100 nm in width.

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Using geometrical considerations, one can estimate that a texture consisting of cones of these dimensions results in an enlargement of the total surface area by a factor of \( \sim 5 - 6 \). Analysis of atomic force microscopy (AFM) images of the same texture as in Figure 1(b) has shown a surface enhancement by a factor of \( \sim 3 \). This value constitutes only a lower limit, since the resolution of the AFM is not sufficient to resolve deeper trenches of the nano-structure. In any case, the removal of the np-Si layer suggests a considerable reduction of the surface area after the SC1 treatment.

To examine the type and quantity of possible defects induced by the black etching process, electron spin resonance (ESR) measurements were performed. Figure 2 shows ESR spectra of b-Si, as-prepared and after SC1 treatment, in comparison with the reference spectrum of a planar substrate. All spectra exhibit a symmetric resonance located at around \( g = 2.0062 \pm 0.0003 \). This \( g \)-factor can be attributed to so-called \( P_{\text{b0}} \) centers, which are Si dangling bonds (Si-dbs) at the (100)Si/SiO\(_2\) interface. The signal intensity correlates with the number of paramagnetic Si-dbs. A Si-db density of \(~ 0.5 \times 10^{13} \) cm\(^{-2}\) was determined from the ESR spectrum of the planar c-Si substrate. This density agrees with typical values in literature for (100)-orientated Si with a natural oxide. We expect an absolute uncertainty of around the same magnitude due to calibration errors and the enlarged surface area of the rough (as-cut) backside of the sample. After the black etching, the same wafer shows an increase of the defect density by a factor \( \sim 7 \), most probably due to the combined and partially counteracting effects of a significant enlargement of the internal surface area and a partial chemical H-passivation of the surface defects with the residual hydrogen which is present in the np-Si layer after the wet-chemical etch process. After the SC1 treatment, the defect density is increased only by a factor \( \sim 3 \) compared to the planar substrate. This factor is similar to the estimated enlargement of the surface area, evaluated from SEM and AFM measurements of SC1-modified nano-textures. From this observation it can be deduced that SC1-modified b-Si exhibits a defect density per effective surface area similar to that of planar c-Si. Thus, we can conclude that defect-rich layers, induced by the black etching process, were removed during the SC1 treatment. Future work will focus on the passivation of the residual surface defects in order to reduce surface recombination.

![Fig. 2: Electron spin resonance (ESR) spectra of b-Si (FZ, p-type, 75-95 $\Omega$cm), as-prepared and after SC1 treatment, in comparison with a planar c-Si substrate. The $g$-factor obtained from the resonance magnetic field (indicated by the vertical line) corresponds to Si dangling bonds at the (100)Si/SiO\(_2\) interface.](image)

\[ g = 2.0062 \]


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Reduced threading dislocation densities in high-T/N-rich grown InN by molecular beam epitaxy

Bernhard Loitsch, Fabian Schuster, Martin Stutzmann, and Gregor Koblmüller

Despite the large potentials of indium nitride (InN) for applications in high-speed electronics, near-infrared photonics, as well as tunable light emitters and absorbers (solar cells), this material has been heavily plagued by fabrication issues (low In–N bond strength, lack of bulk InN crystals). Limited to low–temperature growth and heteroepitaxy on foreign substrates, best–performance InN with highest electron mobilities and lowest threading dislocation densities (TDD ≈ low-10¹⁰ cm⁻²) is, to date, realized in relatively thick (> 1-2 μm) (0001)-oriented films grown on GaN mainly by plasma-assisted molecular beam epitaxy (PAMBE). Like in conventional adlayer–mediated PAMBE growth of nitrides, metal–rich (In–rich) conditions as well as highest possible growth temperature close to the boundary of InN dissociation (< 500 °C) were reported as most appropriate growth conditions. However, these conditions lead to detrimental In-droplets and, more importantly, they have hindered further TDD reduction and minimization of the critical temperature gap between InN and GaN for improved ternary InGaN alloys.

Recently, we reported that unconventional N-rich/high-T growth conditions overcome several of the apparent limitations in InN [1], in analogy to recent observations for GaN growth [2]. All PAMBE growths were performed on semi-insulating GaN/Al₂O₃ templates (Lumilog), using standard effusion cells for group-III elements, and a rf plasma source for supplying activated N. Structural, morphological and electrical transport properties were investigated for all InN films based on rocking curve measurements in high-resolution x-ray diffraction (HRXRD), cross-sectional and plan-view transmission electron microscopy (TEM) and Hall effect measurements. Particular emphasis was put on exploring the effect of growth kinetics on the structural properties (type and density of thread dislocations) near the thermal dissociation limit of conventional metal–rich growth (pyrometer temperature T° ~ 500 °C, equivalent to thermocouple temperature T_TC ~ 550 °C).

The analysis of rocking curve peak widths (ω-scans) of both on-axis and off-axis reflections confirms that mixed-edge type TD are the most dominant type (> 85%) and that their density is highly sensitive to the selected growth conditions. In particular, the peak widths of the mixed-edge type sensitive (201) reflections are strongly reduced toward

Fig. 1: Evolution of FWHM values of the dominant (201) reflection (i.e., corresponding mixed edge–type TDs) as a function of substrate temperature and In flux under fixed N flux. Note the decrease in FWHM toward increased temperature and lower In flux, i.e., near-stoichiometric to N-rich conditions. Data shown here correspond to the typical temperature range of conventional In-rich growth (maximum T_TC ~ 550°C, i.e., T° ~ 500°C).

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increasing temperature $T$ and lower In flux, i.e., near-stoichiometric to N-rich conditions (see Fig.1). Interestingly, very low peak widths are observed for N-rich/high-$T$ grown films even for film thickness far below 1 µm. This behavior is also directly reflected in the resulting electron mobilities, where the highest values of $\sim$1500-1700 cm$^2$/Vs are achieved for thin films grown under high-temperature, near-stoichiometric/N-rich conditions, concurrent with low values of mixed edge-type TD densities.

The overall narrower $(20\bar{2}1)$ -FWHMs observed in N-rich grown films is associated with more effective edge-type TD inclination and annihilation as compared to conventional In-rich growth. This is directly illustrated in the bright-field cross-section TEM micrographs of Fig. 2(a,b), showing that TD annihilation takes place within the very first few hundreds of nm and is completed afterwards. As the surface morphology of N-rich grown films is typically rougher, we developed also two-step growth procedures, where the N-rich grown nucleation layer is smoothened by a subsequent In-rich grown layer (see Fig.2 c,d). Remarkably, the total TDD of such N-rich/high-$T$ nucleated films is as low as $\sim$ 4$x10^9$ cm$^{-2}$ (from plan-view TEM), which is significantly below the typically reported range of $\sim10^{10} - 10^{11}$ cm$^{-2}$.

We further demonstrated that this promising growth window can be extended to even higher temperatures (even above the well-known thermal dissociation limit of In-rich growth) by growing N-rich films up to $T_{\text{C}}$ $\sim$ 620 °C. Quite remarkably, N-rich conditions effectively suppress the commonly large losses in growth rate [1] and enable growth temperatures $> 50$ °C higher than conventional In-rich growth. Interestingly, the trend for decreased TD densities continues at these high temperatures while surface morphologies also tend to become smoother.


Fluctuation-induced luminescence sidebands in the emission spectra of resonantly driven quantum dots

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Self-assembled quantum dots are highly versatile sources of quantum light such as single photons and polarization-entangled photon pairs. The creation of remote entanglement via two photon-interference calls for discrete emitters that produce near Fourier-transform limited single photon wave packets having identical frequency and linewidth. Typically, this is difficult to achieve in solid-state systems since the system undergoes frequency jitter due to fluctuations of the charge environment of the dot and unavoidable coupling to the lattice. For low temperatures and weak optical driving coupling to the lattice is inhibited and the spectral emission lineshape of a single quantum dot is expected to reflect slow fluctuations of the environment which manifest themselves as discrete jumps of the emission frequency and spectral wandering. Complex fluctuations of the local environment can leave rich and unexpected fingerprints in its emission spectrum.

During the past year we explored a new feature that appears in the emission spectrum of individual, resonantly pumped quantum dots that was shown to arise from extremely rare fluctuations that have a dramatic impact on the response of the system [1]. As depicted schematically in fig 1(a), we experimentally and theoretically consider a situation where a narrowband single frequency laser coherently excites an excited discrete interband transition of a single dot, labelled 2 (e.g. p-shell for a single dot), and the emission from the lowest energy excitonic transition, labelled 1 (s-shell neutral exciton for a single dot), is monitored. We developed a non-Markovian quantum dynamical model to describe the response and luminescence spectrum of such a driven, dissipative system in the presence of a fluctuating environment. The model provides excellent quantitative agreement

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with experimental observations, such as the behavior of emission spectrum, linewidths and intensities as a function of experimental parameters (temperature, power and detunings) [1].

As an example of the expected emission spectrum in the absence of a fluctuating environment, fig 1(b) shows the calculated intensity of the emission from level-1 as a function of the emission energy relative to level-1 ($\omega/\gamma_{10}$) and the detuning ($\Delta$) of the excitation laser from level-2 (y-axis). Thereby, the laser energy is fixed and the two exciton levels are simultaneously tuned in energy to replicate the DC Stark shift employed in the experiments. The diagonal line on fig 1(b) is the photoluminescence from level-1, the decrease in intensity for increasing detunings simply arising from the detuning of level-2 from the excitation laser and, thus, a reduced excitation efficiency of the system. The apparent horizontal line at $\Delta = 0$ reflects the very strong enhancement of the intensity at resonance when the excitation laser is fully resonant with level-2.

A typical experimental result is presented in fig 1(c) for comparison with this simple theory. In addition to the basic structure expected from fig 1(b), an unexpected vertical line, labelled FIL on fig 1(c), is observed, that always appears detuned by an energy $\Delta$ from the photoluminescence peak, identical to the detuning of the laser from level-2 ($\Delta$). When a source of fluctuations with a “fat-tail” spectrum are introduced into the model, theory is able to reproduce the experimentally observed spectrum (fig 1(c)). Analysis demonstrated that local fluctuations of the electric field, result in the observation of the FIL peak via a mechanism that is schematically illustrated on fig 1(d). With the excitation laser initially detuned from level-2, fluctuations occasionally result in the system wandering into resonance and generating emission at the energy of the FIL peak. In contrast, when off resonant excitation of the system results in the weak PL signal. The strong increase of the absorption cross section when the system fluctuates into resonance with the excitation laser, compensates for the combined scarcity and brevity of these events.

Most strikingly, we find that the model produces the FIL peak only for scale free (fat tail) fluctuations. In contrast to a Gaussian distribution, a scale free distribution has a finite although very small probability for values arbitrarily far from the most likely position. Due to the small probability for such extreme outliers they typically produce no noticeable effects in experimental measurements. However, for resonant excitation the strong enhancement of the absorption cross section when the system fluctuates into resonance compensates the scarcity of the events and produces the FIL peak. The rarity of extreme outliers makes it also complicated to trace the origin of the fluctuations. For the measurement presented here the origin of the fluctuations was traced to be fluctuations of the potential applied to the gate contact, although intrinsic scale free fluctuations would also produce a signature in the emission spectrum – the FIL peak.

Composition ordering in MBE-grown GaAs-AlGaAs core-shell nanowires


Radial core–shell nanowire (NW) heterostructures currently attract much attention due to their strong potential for novel applications in electronic and photonic devices. When grown epitaxially, such nanostructures are expected to lead to performance enhancements of photodetectors, solar cells, and light emitting diodes. Surface passivation plays an important role in NWs in particular because of their large surface to volume ratio that leads to high surface recombination velocities due to surface states in the band gap.

In the case of GaAs, the near lattice-matched AlGaAs alloy is known to facilitate surface passivation, enhancing the radiative efficiency in optical devices. The ultimate performance and electronic properties of such structures will, however, depend critically on their precise compositional arrangement. Any inhomogeneities, such as alloy composition or dopant fluctuations can disturb structural integrity and affect device performance.

We have investigated the material composition profile within MBE-grown GaAs-Al₀.₃Ga₀.₇As core-shell NWs employing various high-resolution metrology techniques [1].

Fig. 1(a) displays a typical Raman spectral map (step size of 1µm) recorded at T=10 K along the axis of a core-shell NW. A corresponding SEM micrograph of the investigated core-shell NW is shown on the left hand side of the figure. A representative spectrum recorded from the center of the NW (z=5 µm) is also presented in fig. 1(b). Two prominent peaks in the Raman spectra are attributed to the GaAs-like and AlAs-like LO phonon modes. Their intensity and the energetic position remain unchanged over the full length of the NW (> 10 µm). This means that the Al content remains constant within the error of the measurement, indicating on average an excellent long-range compositional homogeneity. The Raman shift of the observed LO modes correspond to an average Al content of x = 0.30 ± 0.03 with great homogeneity over the full length of the NW. An SEM micrograph of the investigated nanowire is shown on the left hand side. The scale bar is 1µm.

![Raman spectra](image)

Fig. 1: µ-Raman spectra recorded (a) along the axis of a single GaAs-AlGaAs core-shell NW and (b) in the center of the NW (z=5 µm). The Raman shifts of LO peaks correspond to an Al content of x=0.30±0.03 with great homogeneity over the full length of the NW. An SEM micrograph of the investigated nanowire is shown on the left hand side. The scale bar is 1µm.

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Despite the good alloy homogeneity along the NW axis interface segregation and local alloy fluctuations are observed along the radial direction using cross-sectional scanning transmission electron microscopy (STEM). Fig. 2(a) shows a STEM high angle annular dark field micrograph recorded along the [1-11] zone axis of a NW with a nominally 24-nm-thick AlGaAs shell. From the contrast in fig. 2(a) we can clearly distinguish the inner NW core, the surrounding NW shell and an amorphous oxidized cap layer (Al-rich regions appear darker than Ga-rich regions).

Remarkably, the NW shell exhibits a six-fold Al-rich substructure along the <112> corners of the hexagonal AlGaAs shell. Fig 2(b) shows 128 x 128 nm$^2$ elemental maps representing the respective elemental distribution of As, Ga, Al and O across the NW cross-section as obtained from a corresponding x-ray energy dispersive spectroscopy (XEDS) map. Detailed XEDS measurement reveal a width of $w = 2.7 \pm 0.2$ nm for the Al-rich substructures with a maximum Al content of $x_{\text{max}} = 0.60 \pm 0.06$. This corresponds to an increase by a factor of 2 with respect to the bulk part of the AlGaAs shell. The origin of this Al enrichment is associated with curvature-induced capillarity diffusion due to the non-planarity of shell growth in combination with an enhanced diffusion of Ga adatoms with respect to Al adatoms.

A modulation of the Al-content is also found along the radial <110> growth directions of the AlGaAs shell. Photoluminescence spectroscopy measurements reveal an $\sim 10^3$ fold enhancement of the quantum efficiency due to inhibition of non-radiative surface recombination, and, in addition, a broadened PL emission band with localized excitonic transitions extending $\sim 150$-30meV below the band gap of Al$_{0.3}$/Ga$_{0.7}$As. Similar sharp line emission is also observed from a reference sample in which a 200-nm-thick AlGaAs layer was grown on a planar (110) GaAs substrate using identical growth conditions. These findings strongly suggest that the sharp line emission arises from deep level defects in the AlGaAs shell under influence of the observed local alloy fluctuations.

Integrated superconducting single photon detectors on III-V photonic nanostructures

Günther Reithmaier¹, Peter Hasch, Jörg Senf, Fabian Flassig, Stefan Lichtmannecker, Thorsten Reichert, Kai Müller, Max Bichler, Michael Kaniber and Jonathan J. Finley

The ability to generate and detect single photons on-chip and to integrate sources and detectors with nanophotonic hardware would represent a major step towards the realization of semiconductor based quantum optical circuits. Superconducting single photon detectors (SSPDs) provide high detection efficiencies, low dark count rates, sensitivity from the visible to the infrared and picosecond timing resolution [1,2]. To achieve these performance metrics, superconducting films with a highly optimised critical temperature ($T_c > 10$ K) and an extremely low thickness ($d_{NbN} < 5$ nm) are required.

As reported in ref [1], we prepared NbN thin films by DC magnetron sputtering on [100] GaAs substrates, optimised their quality, and demonstrated their use for efficient single photon detection in the near-infrared. The interrelation between the Nb:N content (fig 1a), growth temperature (fig 1b) and crystal quality was established. Optimised films exhibited a maximum superconducting critical temperature of $12.6 \pm 0.2$ K for a film thickness of $22 \pm 0.5$ nm and $10.2 \pm 0.2$ K for $4 \pm 0.5$ nm thick films that were suitable for single photon detection [1]. The optimum growth temperature was shown to be $\sim 475$ °C reflecting a trade-off between enhanced surface diffusion, which improves the crystal quality, and arsenic evaporation from the GaAs substrate, as schematically depicted in the bottom panel of fig 1b. Analysis of the elemental composition of these films provided strong evidence that the $\delta$-phase of NbN was formed in optimised samples, controlled primarily via the nitrogen partial pressure during growth. By patterning optimum 4 nm and 22 nm thick films into a 100 nm wide, $369 \mu$m long nanowire meander using electron beam lithography and reactive ion etching, we fabricated single photon detectors on GaAs substrates. Time-resolved studies of the photo-response, absolute detection efficiency, and dark count rates of these detectors as a function of the bias current revealed maximum single photon detection efficiencies as high as $21 \pm 2\%$ at

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4.3 ± 0.1 K with ~ 50 k dark counts per second for bias currents of 98% $I_C$ at a wavelength of 950 nm [1]. As expected, similar detectors fabricated from 22 nm thick films exhibited much lower efficiencies (0.004%) with very low dark count rates ≤ 3 cps. The maximum lateral extension of a photo-generated resistive region in the thicker detectors is estimated to be 30 ± 8 nm, clearly identifying the low detection efficiency and dark count rate of the thick film detectors as arising from hotspot cooling via the heat reservoir provided by the NbN film.

**Fig. 2:** (a) Schematic of samples studied – quantum dot (QD) loaded GaAs waveguide with integrated NbN SSPD. (b) Spatial dependence of detector count rate when scanning the laser spot over the sample with above and below gap excitation. (c) In-situ detected time resolved signal confirming the origin of the detector signal as arising from QD emission measured with a fast timing resolution of 72 ps.

Using optimised superconducting substrates we demonstrated the on-chip generation of light originating from optically pumped micro-ensembles of self-assembled InGaAs quantum dots (QDs), low loss guiding over ~ 0.5 mm along a GaAs-AlGaAs ridge waveguide and high efficiency detection via evanescent coupling to an integrated NbN SSPD [2]. Fig 2a depicts a schematic representation of the samples studied here showing the QD loaded waveguide and integrated NbN SSPD. A typical spatial dependence of the detector count rate as the excitation laser was scanned over the sample is presented in fig 2b for excitation above ($\lambda_{exc} = 632.8$ nm, main panel) and below ($\lambda_{exc} = 940$ nm, insets) the GaAs bandgap. By comparing measurements performed with optical excitation above and below the GaAs bandgap and exploring the temporal response of the system (fig 2c), we show that the detector signal stems from QD luminescence with a negligible background from the excitation laser. Power dependent measurements confirmed the single photon sensitivity of the detectors and showed that the SSPD is about two orders of magnitude more sensitive to waveguide photons than when illuminated in normal incidence [2]. The performance metrics of the SSPD integrated directly onto GaAs nano-photonic hardware confirms the strong potential for on-chip few-photon quantum optical experiments on a semiconductor platform.


Distributed Bragg reflectors (DBRs) grown by molecular beam epitaxy (MBE) using BaCaF$_2$ and GaAs

Anna Köninger¹, Gerhard Böhm, Ralf Meyer, and Markus-Christian Amann

The mirrors used in Vertical-Cavity Surface-Emitting Lasers (VCSELs) need high reflectivities, i.e. about 99.3 % for a top mirror and 99.9 % for a bottom mirror. For this purpose state of the art is to use distributed Bragg reflectors (DBRs) – an alternating sequence of two materials with different refractive indices. The reflectivity of a DBR depends on the difference in refractive indices $\Delta n$ of the materials used. Furthermore, by increasing the number of pairs, reflectivities close to unity can be achieved. However, regarding the heat balance of the device, few layers are preferred as a thick layer stack of course leads to a higher thermal resistance. In this work we used a material combination of GaAs and BaCaF$_2$ to implement a DBR with a high contrast in refractive index ($\Delta n \approx 2$) that can be grown by MBE. Hence, high reflectivities can be achieved by a few number of pairs. Similar approaches of combining III-V semiconductors with group-IIa-fluorides can be found in literature (e.g. [1]). As shown in Fig. 1, the group-IIa-fluorides BaF$_2$ and CaF$_2$ have lattice constants of 0.62 and 0.55 nm, respectively. Thus by using the ternary material, BaCaF$_2$ can be grown lattice matched onto many III-V semiconductor substrates. As the fluorite lattice (left inset) is very similar to the zinkblende lattice (right inset), epitaxial growth should be possible. However, in terms of an ideal interface of BaCaF$_2$ and GaAs as depicted in Fig. 2, it is obvious that there are two possibilities for the fluorite lattice to start growing. As the growth mode of the IIa-fluorides is Volmer-Weber, so to speak island growth, this leads to grain boundaries when two islands with different growth orientations meet each other.

Our aim in using BaCaF$_2$ was to achieve lattice matching and thereby a smoother surface than combining e.g. GaAs and CaF$_2$. However, XRD-measurements of our grown material could not proof pseudomorphic

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growth for BaCaF$_2$ as known from III-V semiconductors. As strain can be released at grain boundaries, the fluorite lattice tends to relax at least partially. Therefore lattice matching can only be assumed. Moreover, it turned out that GaAs layers need a functionalization with fluor to maintain a satisfying adherence of subsequent BaCaF$_2$ layers. This surface treatment was performed in a SF$_6$ plasma. Although XPS-measurements revealed only about 5% of the desired Ga-F bonds, this process step improved the adherence of the layers significantly. With implementation of the fluor functionalization, we managed to grow a stable three pair DBR of BaCaF$_2$ and GaAs on a full-wafer (100) GaAs substrate at 500 °C. Its morphology is depicted in Fig. 3. The visible lines are grain boundaries oriented parallel to the [110] directions. Thanks to its high contrast in refractive indices $\Delta n$, the total thickness of the layer stack is only 1.2 µm with a simulated reflectivity of 99.2%. Furthermore, the high $\Delta n$ leads to a very broad stopband with a bandwidth of 0.5 eV (Fig. 4). In comparison, DBRs made out of combinations of III-V semiconductors show bandwidths of only 0.05 eV at thicknesses of about 7 µm.

As mentioned before, for the application in a VCSEL it is preferable for a DBR to have a small thermal resistance. For a heat generating area of 30,000 µm$^2$, the thermal resistance of the grown BaCaF$_2$/GaAs-DBR was measured to be 24.5 KW$^{-1}$. Thermal radiation was neglected in the calculations whereas heat flow through the DBR could be regarded as one dimensional. Heat spreading in the substrate was considered according to [2]. However, the determined value was four times higher than expected. The reason for this is supposed to be the interfaces which handicap heat conduction through the DBR. In comparison, thermal resistances for both AlGaInAs/AlInAs- and AlGaInAs/InP-DBRs reach values of 29.2 KW$^{-1}$ and 19.8 KW$^{-1}$ respectively.

So in conclusion, our DBR shows an excellent reflectivity behavior. Concerning thermal resistance, it is in the same range with typical III-V alternatives. Possibly the thermal conductivity can be improved by increasing the amount of Ga-F bonds at the BaCaF$_2$-GaAs interface. Consequently, this leads to a lower thermal resistance, if thickness stays the same.


Fig. 3: Photomicrograph of a BaCaF$_2$/GaAs-DBR with three pairs grown by MBE. The visible grain boundaries are parallel to the [110] direction.

Fig. 4: Reflectivity measurements of a BaCaF$_2$/GaAs-DBR and one made out of III-V semiconductor materials. The high difference in refractive indices of BaCaF$_2$ and GaAs leads to a broad spectrum. The bandwidth of this stopband is approx. 0.5 eV.
Characterization of carboxylic-acid terminal organophosphonate self-assembled monolayers on 6H-SiC

Matthias Sachsenhauser¹, Matthias Moritz, Martin Stutzmann, Jose A. Garrido, and Anna Cattani-Scholz

Due to its exceptional stability, strength and biocompatibility, the wide bandgap semiconductor silicon carbide (SiC) is a promising substrate material for applications in the fields of bioelectronics and biosensing [1, 2]. However, an important requirement for using SiC in such applications is the ability to covalently immobilize functional linker molecules on the semiconductor surface.

In this report we demonstrate covalent functionalization of (0001) 6H-SiC surfaces with carboxylic acid (COOH) terminated organophosphate self-assembled monolayers (SAMs). Functionalization was carried out in a two step procedure. First, hydroxyl-terminated SiC was prepared by hydrofluoric acid (HF) etching of the native surface oxide, followed by deposition of 16-phosphonohexadecanoic acid (C₁₆H₃₃O₅P) according to the methods described in [3].

The chemical composition of the surfaces was investigated via X-ray photoelectron spectroscopy (XPS). Fig. 1 shows high resolution scans of the C1s, P2p, and Si2p core level spectra before and after SAM deposition. In contrast to HF etched samples, the C1s signal does not only consist of the substrate signal (≈284 eV) but also features chemically shifted components at ≈286 eV and ≈289.5 eV, which can be ascribed to the hydrocarbons and the carboxylic acid terminal groups of the SAM, respectively. Additionally, a phosphorus peak can be observed after SAM deposition due to the phosphonic acid head group of the molecule. It should be noted that the Si2p core level spectrum is significantly damped after functionalization. The extent of attenuation of the substrate signal can be used to estimate a thickness of $d_{SAM} = 1.3 \text{ nm}$ for the overlying organic layer.

Figure 1: C1s, P2p and Si2p XPS core level spectra of (0001) 6H-SiC substrates before (black curves) and after (red curves) deposition of 16-phosphonohexadecanoic acid. The P2p and Si2p peaks are deconvoluted into doublets due to spin-orbit splitting.

The chemical composition of the surfaces was investigated via X-ray photoelectron spectroscopy (XPS). Fig. 1 shows high resolution scans of the C1s, P2p, and Si2p core level spectra before and after SAM deposition. In contrast to HF etched samples, the C1s signal does not only consist of the substrate signal (≈284 eV) but also features chemically shifted components at ≈286 eV and ≈289.5 eV, which can be ascribed to the hydrocarbons and the carboxylic acid terminal groups of the SAM, respectively. Additionally, a phosphorus peak can be observed after SAM deposition due to the phosphonic acid head group of the molecule. It should be noted that the Si2p core level spectrum is significantly damped after functionalization. The extent of attenuation of the substrate signal can be used to estimate a thickness of $d_{SAM} = 1.3 \text{ nm}$ for the overlying organic layer.

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In order to monitor changes in the resistive and capacitive behavior of the SiC substrates upon surface functionalization, electrochemical impedance spectroscopy measurements were performed (Fig. 2). Before SAM deposition, the spectrum can be fitted by a serial connection of a resistance $R_{\text{ext}}$ and a capacitance $C_{\text{int}}$. Thereby, $R_{\text{ext}}$ is dominating the spectrum in the high frequency limit and includes the resistance of the electrolyte (50 mM Tris, 100 mM NaCl, pH = 7.2), the bulk semiconductor and the connections. The interface capacitance $C_{\text{int}}$ on the other hand dominates at low frequencies and is equal to the capacitance of the semiconductor space charge region $C_{\text{sc}}$. The capacitive contribution of the electrochemical double layer is negligible under the existing measurement conditions. The fitting results for $R_{\text{ext}}$ and $C_{\text{int}}$ are summarized in Table 1. Upon SAM formation no signature of an additional RC-element can be observed in the spectra. However, both, absolute impedance and phase shift to higher frequencies and the total capacitance of the system is clearly reduced (Table 1). $C_{\text{int}}$ can now be interpreted as the space charge capacitance $C_{\text{sc}}$ in series with the capacitance $C_{\text{SAM}}$ of the SAM. Assuming a homogeneous SAM with a voltage independent monolayer capacitance, $C_{\text{SAM}}$ can be evaluated to $1.2 \times 10^{-6} \mu\text{F/cm}^2$. This value can be used to estimate the monolayer thickness $d_{\text{SAM}} = \varepsilon_{\text{SAM}} / \varepsilon_{\text{SAM}} = 1.5 \text{ nm}$ (using the average dielectric constant of 2.1 for long-chain hydrocarbons [4]) which is in reasonable agreement with the thickness obtained by XPS analysis.

In conclusion, we have demonstrated the successful surface functionalization of SiC with carboxylic acid terminal organophosphonates. These monolayers will allow for the attachment of more complex biomolecules, such as proteins or nucleic acids, for future biotechnological applications.

<table>
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<th>$C_{\text{int}}$ [µF/cm$^2$]</th>
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<tr>
<td>w/o SAM</td>
<td>39.7</td>
<td>0.24</td>
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<td>with SAM</td>
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Table 1: $R_{\text{ext}}$ and $C_{\text{int}}$ extracted from the equivalent circuit model depicted in Fig. 2.

Figure 2: Impedance spectra of a 6H-SiC substrate recorded before and after deposition of 16-Phosphono hexadecanoic acid at a bias voltage of $V_{\text{bias}} = 0.5$ V. Full and open symbols represent absolute impedance and phase versus frequency, respectively. The equivalent circuit model depicted in the inset was used for fitting of the impedance data (red lines).
ZnO thin films on diamond

Fabian Schuster¹, Martin Hetzl, Jose A. Garrido, and Martin Stutzmann

The combination of ZnO and diamond has generated some interest in the past with regard to surface acoustic wave (SAW) devices, where the strong piezoelectricity of ZnO and the high Young modulus of diamond perfectly complement each other, and thus, SAW phase velocities as high as 9000 m/s could be realized [1]. However, the performance was limited by the quality of the ZnO film, which had been deposited by reactive magnetron sputtering due to a lack of high-quality epitaxial deposition methods at that time.

Apart from the work mentioned above, no group so far has targeted the investigation and modeling of the diamond/ZnO heterointerface for electronic or optoelectronic applications. To this end, an understanding of the interface was developed in a first step by performing simulations of the electronic band structure. The coupled Schrödinger-Poisson equations were solved self-consistently with the help of the software package NEXTNANO³, using material parameters and realistic impurity doping levels as reported in the literature. For the growth of ZnO on diamond, it makes sense to assume an oxygen termination of the diamond surface, which has the known strong impact on the electron affinity of diamond and, consequently, on the band alignment of the heterostructure. A second important effect is the spontaneous polarization of ZnO, which induces a sheet charge at the heterointerface whose sign depends on the polarity of the ZnO thin film.

![Fig 1: 1D simulation of the band structure at the diamond/ZnO heterointerface. An oxygen termination of the diamond was assumed, while the polarity of the ZnO thin film is a) Zn-face and b) O-face.](image)

The results of the simulation are presented in Figure 1 for the two possible polarities of a) Zn-face and b) O-face ZnO. In the case of Zn-face ZnO, the resulting band bending of the conduction and valence bands leads to the formation of a two-dimensional electron gas (2DEG) at the ZnO-side of the interface. In contrast, a two-dimensional hole gas (2DHG) is expected for O-face ZnO at the diamond-side of the interface. The latter would be the favorable configuration for high-power electronics due to the high hole mobility in

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diamond. In order to ensure a homogeneous formation of the 2D channel, it is crucial to achieve a high interface quality and good structural properties of the ZnO thin film.

ZnO thin films on diamond were fabricated by plasma-assisted molecular beam epitaxy (PAMBE) under ultra-high-vacuum conditions to ensure precise control of the growth process and a low impurity incorporation. For a high structural quality, the substrate temperature was fixed at an elevated value of 540°C and the oxygen flux was fixed at 0.6 sccm at 400W radio frequency power. In order to get an understanding of the different growth regimes, the Zn flux was varied over a wide range. The resulting growth diagram is shown in Figure 2 in terms of growth rate versus Zn beam equivalent pressure (BEP). For low Zn fluxes a linear increase of the growth rate is observed, as expected for the O-rich growth regime. At the stoichiometric point the growth rate saturates, reflecting the transition to the Zn-rich regime where oxygen is the limiting element for the growth.

![Figure 2: Growth diagram of ZnO on diamond with varying Zn flux. The corresponding AFM images show the surface morphology of the thin films with rms roughness included.](image)

The atomic force microscopy (AFM) images show the corresponding surface morphologies of the fabricated ZnO thin films. A trend towards larger crystallites can be observed for increasing Zn fluxes, accompanied by a significant decrease of the rms roughness. Not only the surface morphology, but also the optical properties determined by photoluminescence and absorption measurements (not shown here) allow the conclusion that the Zn-rich growth regime is favorable for high quality ZnO thin films. However, the determination of the polarity has not been completed yet.

Furthermore, the heteroepitaxy of the ternary alloy Zn$_{1-x}$Mg$_x$O on diamond could be demonstrated up to Mg contents of $x = 0.1$ while maintaining good structural properties. Apart from bandgap engineering, this allows a decrease of the intrinsic charge carrier concentration and a higher spontaneous polarization charge at the heterointerface, which both are advantageous for the realization of high-power electronic devices on the basis of Zn(Mg)O/diamond heterostructures.


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Functional polymer brushes on hydrogenated graphene

Max Seifert¹, Lucas H. Hess, Martin Stutzmann, Ian D. Sharp, and Jose A. Garrido

Given its exceptional chemical and mechanical stability as well as unique electrical properties, graphene is an extremely promising platform for biosensors. However, in order to use graphene in a biological environment and to improve sensing specificity and device sensitivity, a well-defined functionalization method for graphene is required.

Recently, we demonstrated that graphene can be directly modified by covalent grafting of polymer brushes using self-initiated photografting and photopolymerization (SIPGP) [1]. It was found that this facile grafting from polymerization, using only UV-light, bulk monomer, and graphene, results in homogeneous polymer brushes on the basal plane of single, few, and multiple layer graphene. The resulting composite is referred to as a polymer carpet, comprised of a single graphene sheet as the substrate and a densely grafted polymer brush. Scanning confocal Raman spectroscopy showed that grafting occurs only from residual defect sites. Furthermore, we found that the photografting process is selective for aromatic monomers (styrene), while acrylates do not result in detectable polymer layer formation. In order to further develop this method, additional control of the polymer layer morphology, as well as introduction of other vinyl monomers, is necessary.

We have demonstrated the use of remote plasma hydrogenation to control the density of surface bound hydrogen and in turn the polymer brush grafting density. The D/G Raman mode intensity ratio can be used as a measure of the density of defects in graphene [2]. Figure 1 (a) illustrates the evolution of the D/G Raman mode intensity ratio after hydrogenation as a function of the remote plasma extraction voltage. The intensity ratio I_D/I_G and, in turn, the amount of surface-bound hydrogen, continuously increases with increasingly negative values of V_acc.

Based on these results, we have applied the SIPGP process to pristine graphene and hydrogenated graphene with different hydrogen site coverage obtained by variation of the extraction voltage in the plasma reactor, as shown in Figure 1(a). The PS layer thickness, as determined by AFM, versus the D/G Raman mode intensity ratio is plotted in Figure 1(b) for polymerization times of 16 h (blue circles) and 8 h (red squares). The layer thickness for pristine graphene (black star) after 16 h of polymerization is shown for comparison. For both polymerization times, the polymer thickness on hydrogenated graphene increases with increasing I_D/I_G ratio. According to the scaling law for grafted polymer layers,[3] the polymer layer thickness increases with increasing grafting density because of surface crowding. Considering Figure 1(a) and (b),

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the large aerial density of hydrogen sites on the surface, corresponding to a high \( I_D/I_G \) ratio, correlates well with the observed systematic increase of the polymer layer thickness. This suggests that C-H sp\(^3\)-sites on graphene act as primary initiation points for polymer chain growth. Further, it demonstrates that the grafting density and layer thickness can be directly controlled by the degree of hydrogenation of graphene over a wide range, with collapsed brush thicknesses from a few nm up to approximately 400 nm.

In order to overcome this limitation of SIPGP-graftable monomers on graphene, we used copolymerization of styrene with acrylic monomers. Although MMA cannot initiate polymerization on bare or hydrogenated graphene, MMA is expected to grow from other organic material, given the presence of abstractable hydrogen atoms and/or already growing chains. Considering the copolymerization reactivity ratios for styrene and MMA, a statistical copolymer, P(S-co-MMA), is expected to form in the presence of both monomers. Figure 2(a) outlines the copolymerization grafting process starting with styrene. SIPGP copolymer grafting was performed in a mixture of bulk styrene (S) and MMA, both on pristine graphene, as well as hydrogenated graphene. Alternatively, we performed a two-step polymerization starting with styrene grafted on graphene to give a PS carpet and a consecutive SIPGP with bulk MMA onto the PS carpets, resulting in a P(S-g-MMA) copolymer layer. Because of the faster polymerization rate of MMA, the consecutive SIPGP using a thin PS primer layer is preferable if a thicker and more accessible PMMA is desired. The presence of MMA monomer units in the resulting copolymer layer could be unambiguously confirmed by DRIFT spectroscopy. As can be seen in Figure 2(b) a strong signal from the carbonyl stretch in MMA shows up at 1731 cm\(^{-1}\) for copolymerized samples compared to pure PS.

Using this approach, it is possible to achieve a well-controlled balance between the density of functional groups on the surface and defect sites in the graphene, opening a synthetic route to functional polymer brushes on graphene.

Fig. 2: (a) Schematic illustration of the copolymerization process via SIPGP. (b) DRIFT spectra of a pure PS brush (red), a P(S-co-MMA) copolymer layer (black) and a P(S-g-MMA) graft-copolymer layer (blue) on graphene. Dashed lines indicate the additional vibrational bands originating from MMA monomer units.

Morphology and doping of laser-sintered Ge nanoparticle thin films

B. Stoib, A. Greppmair, T. Langmann, N. Petermann, H. Wiggers, M. Stutzmann, and M. S. Brandt

Porous, highly doped semiconductors are potential candidates for thermoelectric energy conversion elements. We fabricated thin films of macroporous Ge via short-pulse laser-sintering of Ge nanoparticles (NPs) in vacuum and studied the morphology of the samples. We introduced a versatile method of doping the resulting films with a variety of common dopant elements in group-IV semiconductors by using a liquid containing the dopant atoms. This method is fully compatible with laser-direct writing and suited to fabricate small scale thermoelectric generators. The electrical activation of the dopants was studied by conductivity and thermopower measurements.

We have studied the influence of the laser fluence \( F \) on the morphology and on the macroscopic electrical conductivity \( \sigma \) at ambient conditions of undoped Ge NP thin films. Figures 1(a)–(d) show four exemplary SEM images of laser-sintered Ge NP films, treated with rising laser fluence. As already observed in Si and SiGe samples, our sintering process yields self-organized, meander-like structures which cover the substrate to 60–80%. The macroporous film morphology is similar for a wide range of \( F \), but the characteristic length scale of the meander network grows with increasing \( F \). The mean structure size was evaluated from SEM images by measuring the neck diameter of the meanders as indicated in the inset of Fig. 1(e) for at least 15 positions and taking the average. Figure 1(e) shows that as soon as the typical meander structure is developed, the average width of the meanders grows approximately linearly with \( F \). Figure 1(f) shows \( \sigma \) at room temperature versus \( F \) on a semilog-scale. The conductivity rises rather abruptly by approximately six orders of magnitude and reaches a plateau at \( \sigma = 0.5 \, \text{S/cm} \). For very high pulse energy densities the conductivity breaks down due to increased evaporation of Ge and thus loss of the continuous meander structure. For all further experiments in this work, we use a pulse energy density of \( 50 \, \text{mJ/cm}^2 \), leading to a conductivity in the plateau region.

As an alternative to the usually pursued approach of doping NPs during their growth in the gas phase, we have developed a method to accurately dope our laser-sintered films with group-III or -V elements by immersing the deposited NP film prior to laser sintering into a

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liquid containing the dopants. Due to the high porosity of the NP film and the good wetting behaviour of aqueous solutions observed after HF etching, the liquid penetrates the film completely. After flushing the films with dry N₂, the dopants remain in the NP layer. The subsequent laser sintering process incorporates them into the larger Ge crystallites formed. A particular benefit of our method using NP thin films as precursors for the host material is their high porosity, allowing the doping fluid to penetrate deeply into the film. The activated dopants reach concentrations strongly changing electronic transport while maintaining the morphology presented in Fig. 1. Figure 2 shows the effect of immersing undoped Ge NP films prior to laser sintering in solutions containing P, As, Sb or Ga in various concentrations on the samples' ambient thermovoltage and electrical conductivity. For each series one reference sample, which was only exposed to deionized water, is also shown. All nominally undoped samples have a thermovoltage of +17 mV corresponding to a Seebeck coefficient of +300 μV/K and a conductivity of 10⁻¹ S/cm, in agreement with Fig. 1(f). Increasing the dopant concentration leads to changes of S and σ for all dopants investigated. The thermovoltage of thin films exposed to low dopant concentrations stays close to the value of the undoped reference. For all group-V donor elements, an increase of the dopant concentration leads to a more or less abrupt change of sign in the thermovoltage at a certain dopant concentration depending on the element, accompanied by a rise of the conductivity by several orders of magnitude. The thermovoltage changes sign when the incorporated and activated dopants compensate the valence band near defects, which are known for polycrystalline Ge. This compensation also minimizes the charge carrier density. The resulting minimum in the conductivity is best seen for P doping. The lack of knowledge about the actually incorporated amount of atoms prohibits a quantitative evaluation of the defect density so far. Further increasing the concentration, the absolute value of the thermovoltage drops again. As expected for a group-III acceptor, Ga doping does not lead to a change of thermopower sign, but a steady decrease of the thermovoltage is observed for increasing Ga concentration. This also is accompanied by a rise of the conductivity. A comparison of the thermovoltage and the conductivity data shows the expected systematic anticorrelation of S and σ, clearly demonstrating the applicability of laser-assisted wet-chemical doping to NP systems and Ge NPs in particular.


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Device Physics
AlGaInAsPSb-based high-speed short-cavity VCSEL with single-mode emission at 1.3\(\mu\)m grown by MOVPE on InP substrate

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We present the first InP-based short-cavity Vertical-Cavity Surface Emitting-Laser (SC-VCSEL) with an AlGaInAsP / GaInAsP active region and a regrown GaAs\textsubscript{0.5}Sb:C / Ga\textsubscript{0.47}InAs:Si buried tunnel junction (BTJ), which serves as current aperture, grown by LP-MOVPE (Fig. 1). We achieved over 1 mW single-mode continuous-wave (cw) emission at around 1.3 \(\mu\)m wavelength and room-temperature (Fig. 2). The small-signal modulation bandwidth exceeded 7.5 GHz (see Fig. 2), which is appropriate for 10 Gb/s data transmission, and the series resistance was as low as 24 \(\Omega\). Both values already indicate better performance than comparable MOVPE-grown VCSELs based on the AlGaInAs standard material system [1].

Figure 1: Sketch of the SC-VCSEL. The type-II band alignment between GaAsSb and GaInAs (the material combination for the buried tunnel junction) and the standing field patterns of the optical wave are also illustrated.

InP-based BTJ-VCSELs are necessary to satisfy the rising bandwidth demand of access networks like fiber-to-the-home and passive optical networks, since they emit in the O- & C-band and have reduced optical losses due to the tunnel junction, which converts holes to electrons. Hence, only a small amount of the lossy p-cladding between the active region and the tunnel junction remains and most of the material in the cavity consists of \(n\)-InP (see Fig. 1). Since sufficient high p-doping with a segregation-stable dopant like Carbon is hardly achievable with Ga\textsubscript{0.47}InAs by MOVPE, we exchanged this material with GaAs\textsubscript{0.5}Sb and could realize a p-doping of higher than 5\(\times\)10\textsuperscript{19} \(\text{cm}^{-3}\). Furthermore, the type-II band alignment in combination with Ga\textsubscript{0.47}InAs (see Fig. 1) decreases the tunnel

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barrier, but requires also the implementation of an AlGaInAsSb:C grading to inject the holes into the active region. Here, we used five GaInAsP quantum wells in combination with AlGaInAsP barriers. GaInAsP was chosen to remove the Aluminum from the well material and, hence, decrease the non-radiative SH-recombination-rate.

The growth was carried out with an AIX 200/4 MOVPE system in a temperature range from 650°C to 500°C at 150 mbar. As precursors TMGa, TMAl, TMIn, TMSb, CBr4, Phosphine, Arsine and Silane were used. Characterization of the layers was performed with XRD, PL, Hall- and reflection measurements. For in-situ reflectance a Laytec “EpiTT” was used.

To enhance the modulation speed, dielectric top and bottom mirrors were evaporated, which reduce the cavity length due to the higher refractive index difference [2]. The rather high threshold current of 4.2 mA can be explained by the detuning of the cavity from the designed wavelength of 1.31 µm. By implementing a phase matching layer between the top DBR we expect even increased device performance. Further details can be found in [3].

[1] A. Mereuta, “10Gb/s and 10-km error-free transmission up to 100°C with 1.3-µm wavelength wafer-fused VCSELs”, Optics Express, Vol. 17, pp. 12981-12986, July 2009


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30 Gbps error-free optical links based on 1.3 μm short-cavity VCSELs

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Vertical-Cavity Surface-Emitting Lasers (VCSELs) exhibiting emission in the optical O-Band (1260 – 1360 nm), data-rates beyond 25 Gb/s, and high energy efficiencies have been sought-after light sources for evolving 100G-Ethernet solutions in access- and metropolitan-networks. As the best reported error-free optical links based on 1.3 μm VCSELs have just reached maximum bitrates of 12.5 Gb/s and energy-to-data ratios above 1 pJ/bit [1-2], a performance gap has to be closed in order to successfully implement standards like “100GBase-LR4” specifying the error-free transmission over 10 km of single-mode fiber (SMF) in a parallel scheme of four 25G-channels in the 1.3 μm wavelength range. Here, 1.3 μm high-speed short-cavity (SC-) VCSELs exhibiting the required properties are presented. These devices enable the first error free data-transmission over 10 km of standard single-mode fiber at data-rates up to 30 Gb/s. For such a link, the lowest EDDR of 27 fJ/(bit·km) is reported, making these devices the most energy-efficient VCSELs available to date.

Fig. 1a) shows the layout of a 1.3 μm SC-VCSEL. The implementation of two dielectric mirrors with a low penetration depth of the optical field yields a short effective cavity length of 2.4 μm, a reduced photon lifetime, and a high small-signal modulation bandwidth $f_{3dB}$ of 15 GHz [3]. For a detailed discussion of the optical, electrical, and thermal design of SC-VCSELs as well as a description of all device components, the reader is referred to [4]. Fig. 1b) depicts the current dependent optical output-power and the device-voltage of a SC-VCSEL with a 3 μm current-aperture operated at room-temperature. Maximum output powers of 2.8 mW and side-mode suppression ratios beyond 50 dB are achieved at roll-over current (see inset). A rather low threshold-current of 500 μA and a high slope-efficiency of 0.5 W/A allow high wall-plug efficiencies of 28% to 32% in the low current regime from 1.5 mA to 5 mA (see Fig. 1c). For such biasing, the dissipated power is below 5 mW and low EDDRs can be expected for the large-signal modulation conducted in the following section.

Fig. 1: (a) Perspective view on short-cavity VCSEL with indicated components (b) L-I-V characteristics and optical spectrum ($I_{DC} = I_{RO}$) at 20°C (c) Wallplug-efficiency and dissipated power vs. current for same device with an aperture diameter of 3 μm.

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Fig. 2a) shows the bit-error rate (BER) versus received optical power for the transmission of 25 Gb/s NRZ bit-patterns with a pseudo-random bit-sequence (PRBS) of $2^7$-1. For both back-to-back (B2B) configuration and 10 km SMF-link, error-free transmissions with clear open eyes (see insets) were achieved. Measured signal-to-noise ratios (S/N) are 4.5 for B2B and 5.0 in the 10 km case. For the indicated bias-conditions in Fig. 2a), the total power-consumption of the VCSEL, including the injected RMS RF-power, is only 6.7 mW converting into the lowest to date reported EDDR of 27 fJ/(bit·km). In order to exclude any pattern-length dependence of the BER due to VCSEL memory effects, also longer bit-patterns with a PRBS of $2^{23}$-1 were investigated (Fig. 2b). Like before, error-free transmission (B2B & 10 km) was achieved. Therefore, no strong pattern-length dependence was observed. Last, but not least, error-free transmission at 30 Gb/s over up to 10 km of SMF was demonstrated for a slightly increased DC VCSEL-bias (see Fig. 2c). This result pushes the bit-rate benchmark for 1.3 μm VCSELs by almost a factor of three and finally will allow the energy-efficient implementation of aforementioned and many other applications.

![Figure 2](image.png)

**Fig. 2:** Error-free data-transmission at 25°C using a 1.3-μm high-speed short-cavity VCSEL. Details on the link are indicated.

We presented 1.3 μm high-speed short-cavity VCSELs with a novel short-cavity design featuring low threshold currents (500 μA) and high wall-plug efficiencies (~30%). For the first time, error-free data transmission has been presented for bit-rates up to 30 Gb/s and link lengths up to 10 km. The highest to date reported EDDR of 24 fJ/(bit·km) will particularly allow the energy-efficient implementation of 100G-Ethernet solutions.


Investigation of laser performance of InP-based short cavity VCSELs with stacked active region

Alexander Andrejew, Michael Mueller, Ralf Meyer and Markus-Christian Amann

In the last decade information flow around the world increased immensely, the conventional methods of information transfer via copper wires are not able to cope with the increasing bandwidth anymore. Therefore, optical fibers are used for the information transfer, in the future with the upcoming fiber-to-the-home (FTTH) application the optical fiber network should be extended down to the end-user. For this application cheap laser-diodes with low power consumption and high modulation bandwidth are essential, therefore near-infrared, Indium Phosphide (InP) based, vertical-cavity surface-emitting lasers (VCSEL) with emission wavelength at 1.55µm are highly desired, since they fulfill all the necessary requirements.

In the recent work device performance of Short Cavity (SC) VCSELs with innovative stacked active region is investigated.

The decisive parameter for the high-speed performance of a laser is the resonance frequency, which increases with decreasing photon lifetime and cavity length. In a VCSEL the effective cavity length is determined by the epitaxial thickness of the resonator and the penetration depth of the light into the mirrors, adding up to a few micrometers. Fig. 1 (a) shows a schematic cross section of an InP-based short cavity VCSEL as described in [1]. The aperture of the device, necessary for the current confinement, is defined by the buried tunnel junction (BTJ), which is placed in the node of the electrical field to reduce absorption. To improve the high-speed performance of the device the cavity length needs to be minimized. This is achieved by using a very short epitaxial cavity and by applying highly reflective dielectric distributed Bragg reflectors (DBR) (reflectivity >99.5%) to reduce the light penetration into the mirror and thereby reducing the effective cavity length. The active region of a conventional InP-based SC VCSEL consists of 6 to 7 compressively strained AlGaNAs/GaInAs quantum wells (QW) which are placed in the antinode of the electric field. This results in a relative confinement factor (between 1 and 2), which increases for thinner active regions, e.g. with less QWs. However, this also results in lower gain and output power. The possible solution here is to use a stacked active region. Stacked active region means that a series circuit of two or more separate active regions is employed in the laser diode. In this arrangement the p-side of one active region is connected to the n-side of the next one using a tunnel junction. For the VCSEL each active region in a stack is placed in a separate antinode (see Fig. 1 (b)), yielding an increase of

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Fig. 1: (a) Cross section of a Short Cavity VCSEL with BTJ. (b) Refractive index profile and standing wave pattern of the stacked active region in SC VCSEL
the relative confinement factor while keeping the total number of QWs constant (1.97 for a stack of two active regions with 3 QWs each, compared to 1.84 for a single AR with 6 QWs). Another advantage is the expected reduced threshold current (proportional to the number of QWs) at the cost of an increased voltage drop, which should result in lower ohmic losses and increased differential quantum efficiency.

To investigate the impact of the stacked active region a stacked device with 2×3 QWs and a reference with 1×6 QWs were fabricated. From the L-I-V measurements (output power and voltage vs. current, see Fig. 2) the relevant optical and electrical parameters were extracted: the differential quantum efficiency (emitted photons to injected electrons ratio) of the stacked active region device was found to be 80% (comparing to 57% of the reference). The voltage was doubled as predicted by the theoretical model, the threshold current, however, was found to be twice as high for the stacked AR device (4 times higher than expected). The reason for this behavior was found to be the extremely high current spreading induced by the unstructured tunnel junction (compare Fig. 1(b)). A current spreading length of 6.65 μm and an estimated threshold current density of 1632 A/cm² were calculated from the fit shown in Fig. 3 (a) for the stacked AR device (for the reference: 1.25 μm and 2944 A/cm², respectively), which means that the threshold current density is halved as expected, whereas the threshold current is doubled due to a 4 times larger pumped area. From the impedance of the device the spreading and layer resistance were extracted – 50 Ω for the reference and 66 Ω for the stacked AR device, which also implies higher current spreading in the stacked AR device. Additionally it should be mentioned that the current spreading is different in the ARs in the stack, causing a degeneration of laser performance, which can be seen e.g. in the irregular modulation response (Fig. 3(b)) of the stacked AR device (red points), which also causes lower cut-off frequency of 12 GHz. The reference on the other hand achieved excellent high-speed performance with 15 GHz cut-off frequency at 35°C.

Both investigated devices showed excellent performance in general. The inferior performance of the laser with stacked AR was found to be due to extremely high current spreading, which means that the performance can be further improved by reducing the spreading, e.g. by structuring both tunnel junctions and applying 2 overgrowths.

Fig. 2: L-I-V characteristics of devices with 4 μm aperture at 20 °C

Fig. 3: (a) Model for extracting the current spreading. (b) Modulation response of both VCSELs.
Record single-mode, high-power VCSELs at 1.55 µm by inhibition of spatial hole burning

Tobias Gründl, Pierluigi Debernardi, Michael Müller, Christian Grasse, Philipp Ebert, Kathrin Geiger, Markus Ortsiefer, Gerhard Böhm, Ralf Meyer, and Markus-Christian Amann

Vertical-cavity surface emitting lasers (VCSELs) based on InP with remarkable single mode output powers are presented. It is shown, that a precise choice of the diameters of the ring geometry of the bottom GaInAs intracavity contact layer (p-side) is highly beneficial for overcoming spatial hole burning and for increasing current injection efficiency. As a result, an optical output power of approximately 8 mW at room temperature on the basis of a 7 µm wide aperture could be realized. Side mode suppression ratios (SMSRs) exceeding 50 dB offer highly single-mode (SM) lasing behavior with a continuous electro-thermal tuning of the emission wavelength of 8 nm.

Vertical-cavity surface emitting lasers (VCSELs) originally invented by Iga [1] have undergone numerous modifications and optimizations over the past decade. Based on GaAs, InP and even GaSb, they offer a big variety of applications starting from short-range data-communication at 850 µm [2] to energy efficient, long-distance data-transmission at 1.55 µm [3] and last but not least gas sensing at all spectrally important wavelengths in the MEMS-VCSEL design ranging from 1.55 to 1.95 µm [4]. We found out that the overlap of the p-side GaInAs contact layer (CL) of the VCSEL (shown as blue, filled layer in Fig.1) with the circular geometry of the buried tunnel junction (BTJ, shown as black, empty circle) has a strong influence on the current injection efficiency and the spatial hole burning of the laser. The parameter $\Delta_{CL}$, shown in Fig.1, describes the overlap between the CL and the BTJ, depending on its sign.

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Widely tunable, polarization stable BCB MEMS VCSELs emitting at 1.55 μm with integrated sub-wavelength gratings based on InP

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Introduction - The established short-cavity design of the present Vertical-Cavity Surface-Emitting Lasers (VCSELs) based on InP has already proven to be highly capable for fiber-Bragg-grating applications, high-speed data transmission, gas sensing and spectroscopy. Most frequently discussed restrictions regarding optical output powers, modulation bandwidths or tuning ranges could recently be successfully improved by appropriate laser designs [1,2,3]. However, due to the cylindrical symmetry of the device the transverse polarization behavior could not reliably be stabilized. Several attempts offering single polarization mode behavior in VCSEL devices have already been discussed [4,5]. Due to technological constraints, in case of tunable devices, we focused on the implementation of a sub-wavelength-grating (SWG). In our studies a short-cavity InP-based half-VCSEL (without top DBR) is combined with an externally mounted GaAs-based membrane-DBR with integrated SWG.

Device Structure - The VCSEL basis structure consists of 7 compressively strained AlGaAs quantum wells (QWs) with $g/a = 2.5\%$ pseudomorphic strain (Fig. 1). The physical length of the cavity of the half VCSEL is 2.7 μm. Whereas fixed wavelength devices show excellent single mode behavior for apertures up to 5.5 μm in diameter [1] MEMS VCSELs (MEMS = Micro-Electro-Mechanical-System) can go even higher. In our case a 10 μm BTJ aperture has been investigated at 20°C. The cavity resonance is designed for 1555 nm with a mode-gain offset of the active region of 24 meV. The whole VCSEL mesa is encapsulated by benco-cyclo-butene (BCB) for lowering the pad parasitics and increasing the modulation bandwidth $f_m$. Former studies on SWG-free MEMS VCSELs have already shown a modulation bandwidth of 6 GHz [6]. The back DBR consists of fluorides and sulfides, buried by a 60 μm thick gold electroplating. More details on the active element can be found in [1]. The GaAs-based membrane-DBR consists of 16.5 pairs of AlGaAs/Ga(In)As layers. An implemented gradient in strain caused by indium offers a pre-buckling of the membrane during process after substrate removal. This is accomplished with the Indium concentration of the implemented GaInAs layers varying from 5 to 2 %. The total 4 μm thick DBR is partitioned in a 50% strained upper part and a 50% unstrained lower part. The SWG is transferred via resist mask dry chemically into the last

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crystalline GaAs layer facing the air gap and the VCSEL eye. Its duty-cycle is 0.5, the period 300 nm and the etching depth 130 nm.

**Results and Discussion** - Simulations on the basis of the VELM code [7] have proven a difference in threshold gain regarding the TE and the TM mode of 20 to 30%. Polarization dependent reflectivity measurements on the GaAs membrane confirmed the TE suppression by 1.6 dB decrease in signal (Fig. 2a). The laser light of a 10 µm BTJ (BTJ = Buried Tunnel Junction) laser was coupled into a single mode fiber (SMF) whereas the polarization was adjusted using a polarization controller and beam splitter. The output power of lasing mode and the suppressed one could be measured simultaneously. As can be seen from the \( P-I \) curve in Fig. 2b there is no polarization switching when changing the laser current. Due to several loss mechanisms during measurement only a maximum of 0.8 mW of the lasing mode could be detected. By contrast when using a multi mode fiber (MMF) 4 mW were achievable. When actuating the membrane electrothermally a wavelength shift of more than 20 nm occurs due to cavity tuning with a center wavelength of 1550 nm (Fig. 2c). A driving current of \( I_L = 30 \) mA has been used. By scanning the accessible wavelength range in steps of 2 nm a polarization suppression ratio of TE/TM exceeding 20 dB in average could be observed over the whole tuning range.

**Conclusion**: We presented a polarization stable Micro-Electro-Mechanical-System VCSEL with an integrated sub-wavelength-grating (SWG). It offers an output power of the TE mode of 0.8 mW in a SMF and 4 mW in a MMF. The single transverse mode can be tuned continuously over more than 20 nm with a center wavelength of 1550 nm. Over the whole tuning range the polarization suppression ratio of TE/TM exceeds 20 dB in average.


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Type-II quantum well lasers based on InP

Stephan Sprengel\textsuperscript{1}, Christian Grasse, Peter Wiecha, Alexander Andrejew, Tobias Gruendl, Gerhard Boehm, Ralf Meyer and Markus-Christian Amann

Lasers operating in the wavelength range from 2 to 4 µm have many applications such as medical sensing, bio sensing and contactless highly sensitive gas sensing [1] - [3]. For this range, the dominant devices are type-I lasers based on quaternary GaInAsSb quantum wells [4] and interband cascade lasers [5]. Both are based on the GaSb or InAs material platforms. Despite the variety of applications, the development status of these lasers is rather low, compared to lasers for example in the telecommunication area.

An alternative to these lasers are type-II InP-based lasers. These lasers use the type-II band alignment between GaInAs and GaAsSb, to create so-called W-shaped quantum wells (see Fig. 1) in which, electrons and holes are separated in different layers, therefore enabling transition energies below the band gap energy. Unfortunately, separation of carriers also reduces the coupling strength between electrons and holes, hence more carriers are needed to achieve the same emission strength as in type-I devices. To achieve a strong coupling and long emission wavelength at the same time, the GaInAs and GaAsSb layers have to be very thin and highly strained. This leads to a challenging growth since the layer thicknesses are in the order of a few nanometers. Nevertheless, photoluminescence emission up to a wavelength of 3.9 µm could recently be demonstrated [6,7]. This exceeds the limit for InP-based type-I light sources (2.3 µm) by far and is close to the maximum wavelength theoretically predicted (4 µm) for type-II quantum wells on InP [8].

Recently we demonstrated the first type-II InP-based lasers. The lasers contain 1 to 6 W-shaped quantum wells separated by tensile strained barriers for strain compensation. These are surrounded by wave-guiding layers, made of GaAsSb or GaInAs. Additionally InP or AlInAs cladding layers on top and bottom, enable current injection and confinement of the optical field.

The laser structures were grown on \textit{n}-doped (100) InP substrate, using two Varian GEN-II solid source MBEs. In addition to the group III elements Al, Ga and In, one MBE is equipped with As\textsubscript{2} and Sb\textsubscript{2} cracker cells, the other one with As\textsubscript{2} and P\textsubscript{2} cracker cells. The first one was used for the growth of active region and waveguide, the second for the top and bottom cladding layers. A vacuum transfer

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\textbf{Fig. 1:} Band structure of a W-shaped active region. Wave functions for electrons and holes are indicated.

\textbf{Fig. 2:} Photoluminescence spectrum of a W-shaped active region for different excitation powers.
chamber connecting both machines allows to grow antimonides as well as phosphides, without the need to have both Phosphorus and Antimony in the same chamber, and without exposing the structure to air between the growth steps.

![Diagram of a laser chip](image)

**Fig. 3:** Schematic picture of the processed edge emitting ridge waveguide laser.

A schematic picture of the laser chip is shown in Fig. 3. After growth, the structure was processed into ridge waveguide lasers by etching down the top cladding layer. The etched surface was passivated with SiO$_2$ and top and bottom contacts were evaporated. The lasers were cleaved into different lengths and mounted epi-side up on a copper heat sink. The facets were left uncoated.

Up to now, the range from 2.2 µm to 2.6 µm can already be covered by InP-based type-II lasers [6]. Spectra of several lasers are displayed in Fig. 4. The devices are still at a very early stage, nevertheless, continuous wave operation was demonstrated up to 30°C at a wavelength of 2.55 µm. The threshold currents per quantum well are around 220 A/cm$^2$, which is higher than for their GaSb counterpart, but a significant improvement is expected from design optimization.


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InP-based micro-cavity LEDs with GaInAs/GaAsSb type-II active regions emitting up to 3.5 µm

Peter Wiecha¹, Christian Grasse, Stephan Sprengel, Tobias Gruendl, Ralf Meyer, and Markus-Christian Amann

Light sources with emission wavelengths in the range from 2 to 4 µm are of particular interest for absorption spectroscopy purposes, as many gases like CO, CO₂, CH₄ or CH₃Cl exhibit strong absorption lines in this wavelength regime. Beyond 2.3 µm emission wavelength, GaSb and InAs based devices are commonly used for portable applications. However, it would be favourable to avoid these expensive substrates and employ InP instead, whose thermal conductivity is superior and whose device technology is well established due to the telecommunication industry.

Fig. 1: Layer structure of the fabricated resonant cavity LEDs (middle). a) shows the band structure of a superlattice (SL) active region while the energy diagram of the LED containing a "W"-shaped QW is sketched in b).

Taking advantage of the high band offsets between InAs and GaSb, InP-based GaInAs / GaAsSb type-II structures are supposed to allow electron-hole recombination at longer wavelengths than the strain limited type-I emission on InP substrate [1]. GaInAs / GaAsSb type-II QWs were therefore implemented in resonant cavity light emitting diodes (RC-LEDs) on InP substrate (see Fig. 1). Superlattice and “W”-shaped QWs with emission wavelengths around 3 µm were compared [2]. However, for such active regions an increase in wavelength is inevitably correlated with a reduction in wave-function overlap, therefore thorough optimization of the type-II quantum well structure was necessary, which consequently allowed to improve the performance of the type-II LEDs (output power, thermal stability) and to enlarge the emitted wavelength. Even at $T=80^\circ C$, up to 3.5 µm of electroluminescence could be realized under continuous wave operation (see Fig. 2) signifying the longest reported direct emission from this substrate [3].

Despite the reduced wavefunction overlap integral, the grown LEDs exhibit superior output power (up to ~120 µW at 20°C and ~80 µW at 80°C) and temperature stability compared to available GaSb and InAs based devices [4] in the same wavelength range (using

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e.g. InAsPSb). This renders the presented type-II RC-LEDs very promising for gas-sensing or other applications.

Nevertheless, an efficiency droop at increasing driving currents was observed (see fig. 3). This behavior is likely to be caused by the small wave-function overlap integral of bound states in the active region, which after Fermis golden rule results in a reduction of the transition rate. The optical output power versus driving current could be modeled by including a critical carrier density $n_0$ into the rate equation for recombination (ABC-model) like developed for nitride LEDs [5].

Further improvement of the GaInAs / GaAsSb type-II active regions - in device performance as well as in the range of emission energies - seems still possible. Particularly an implementation of several stacked type-II active regions in vertically emitting lasers using tunnel junctions may be promising. Finally can be concluded, that evidently neither the wavelength range accessible from within the InP material system nor the potential in output power at these wavelengths is exhausted yet.

**Fig. 2:** Spectra of an SL-LED and a W-LED at different temperatures, both emitting in cw-operation beyond 3.0 µm.

**Fig. 3:** Measured output power and fit for the two LEDs shown in Fig. 2.


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THz emission by difference frequency generation in quantum cascade lasers with a Čerenkov phase matching scheme

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The terahertz (THz) spectral range (λ = 30 – 300 μm) has drawn wide attention due to its many possible applications in the fields of medicine, homeland security and radio astronomy. Currently available THz sources based on free electron lasers and difference-frequency generation (DFG) mixing CO₂ lasers are large and inefficient, while THz quantum cascade lasers offer the advantage of a compact semiconductor laser but still require cryogenic cooling for operation. We present a device based on intra-cavity difference frequency generation for THz emission at room temperature. This is achieved by an implemented Čerenkov phase-matching scheme, which enables the device to efficiently extract THz radiation along the entire length of the laser for broadband THz output.

Similar to previously reported quantum cascade lasers (QCLs), the active region provides dual-wavelength mid-infrared (MIR) emission at frequencies ω₁ and ω₂ and is grown on a semi-insulating InP:Fe substrate [1-4]. Both MIR modes are confined to the waveguide. A nonlinear (NL) section with susceptibility χ(2) is integrated into the active region and is optimized for difference-frequency generation among the MIR pump wavelengths. In this region the electric fields from the optical pumps excite a nonlinear polarization wave in the medium, which propagates at a higher phase velocity than the radiated THz mode. This describes the Čerenkov condition, which causes generated radiation to be emitted at the Čerenkov angle θc relative to the direction of kNL [2]. This Čerenkov phase-matching condition can be realized in a conventional InP/GaInAs/AlInAs material system. The crucial part is the implementation of a semi-insulating InP:Fe substrate, which exhibits a higher refractive index for THz frequencies than for MIR wavelengths. It acts as a leaky waveguide for the THz wave, without affecting the waveguide of the MIR modes. Simultaneously, its semi-insulating character yields the very low free carrier absorption. This enables the device to emit

Fig. 1: Schematic drawing of the THz device. Top gold contacts are shown in yellow, insulating Si₃N₄ layer in blue. Doped InP layers are shown in grey/green and active regions emitting at ω₁, ω₂ with integrated nonlinearity χ(2) are shown in red. The semi-insulating InP:Fe substrate is polished to an angle of 30°.
at very long wavelengths. Samples were processed into ridge waveguide lasers with the approximate dimensions of 18 μm x 2 mm. To avoid total internal reflection of the THz radiation, the semi-insulating substrate was polished to an angle of 30°.

Power measurements of the device are presented in Fig. 2 and show THz peak output power up to 60 μW at 3.5 THz. For this wavelength the device achieved a MIR to THz conversion efficiency of 550 μW/W². Spectral measurements for THz emission and the MIR pumps showed emission at 3.5 THz and is in perfect agreement with the MIR pump beams emitting at 9.43 μm and 10.6 μm. In all measurements the QCL was operating at high temperatures T = 298 K. For our device the Čerenkov angle was calculated to be 20°, which was proven experimentally. Its performance exceeds previous THz DFG QCLs.

In conclusion, we successfully demonstrated a THz source, based on intra-cavity difference-frequency generation and a Čerenkov phase-matching scheme. THz emission at 3.5 THz was demonstrated with the device operating at room temperature. The implementation of the semi-insulating substrate acting as a leaky THz waveguide minimized free carrier absorption, led to an output power of 60 μW and a power efficiency of 550 μW/W². Further device optimization promise THz radiation with higher output power and higher power efficiency at room temperature.


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Miniaturized optical nanoparticle sensor using laser beam shaping and Fresnel ring lenses

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Development in the field of detecting nanoparticles in air has been going on for several decades with recent success in detecting viruses with new approaches, e.g. whispering gallery mode resonators [2-4]. Yet there remains the need for a highly sensitive, small-size and cost effective online sensor [1]. The measurement technique regularly used is to analyze laser light at multiple angles scattered by particles passing through the laser beam. However, when these devices are being miniaturized, the detection is usually limited to particle sizes >> 100 nm in diameter [5,6].

In previous works we reported on a setup using spherical ring mirrors to collect a high amount of scattered light in solid angle intervals to increase the sensitivity significantly. Although some excellent results could be achieved with this technique, it is limited by aberration. [7].

In current research we developed a setup of a potentially mobile device consisting of a 450 nm, 10 mW laser diode, highly sensitive silicon avalanche photo diodes and two Fresnel ring lenses (see figures 1, 2). These concentrical rings collect the scattered light at two separate solid angle ranges (~18°-32° and ~32°-42°).

Fresnel lenses have the advantage of a higher diameter to focal length ratio than normal lenses and therefore allow a shorter optical distance between scattering particle and collecting optics. This allows a smaller setup and the collection of scattered light in a wide solid angle interval. Thus the detected signals get magnified by a factor of > 100. The particle size is determined from the ratio of the signals using Mie theory.

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Ideally the particles cross the laser beam at the focal point exhibiting the maximum intensity. Practically, however, the gas stream carrying the particles is not straight linear and therefore particles cross the laser beam longitudinally and transversally lateral as well (see Fig. 3). Even if the intensity of the laser beam is smaller in lateral positions, the scattered light will still be collected and thus leads to an undesirable lower signal to noise ratio. Ideally only signals from particles crossing the laser beam at the maximum intensity having the maximum SNR result in a scattering signal. Hence the laser beam has been shaped by a bar-shaped aperture in the laser optics, blocking lateral laser light.

Starting from a certain longitudinal distance the image of the scattered light on the detector exceeds the detector area and signal loss occurs. Thus the ratio of the two signals is not the same as in the focal point and a wrong particle size is determined. To overcome this problem, only signals up to a maximum distance to the focal point are accepted. This is done at signal processing by limiting the acceptable time of a scattering signal which directly relates to the particle’s position. Additionally we use a slip-shaped aperture at the laser optics to cut most lateral parts of the laser beam, thus providing uniqueness in particle size identification.

Measured signal-to-noise-ratios using 150 and 300 nm sized polystyrene latex particles are significantly above 10. The expected minimum sensitivity lies at particles with diameters around 80 nm. Still the whole setup (excluding electronics) would still fit in every ordinary pocket.

References:

The influence of lateral gates on the quantum capacitance of graphene nanoribbons

Stefan Birner¹, Rafael Reiter², Ulrike Derra³, and Christoph Stampfer³

Due to the low carrier density in the near vicinity of the charge neutrality point, graphene exhibits quantum capacitance effects [1, 2]. In advanced graphene nanodevices lateral side gates play an important role. For example, they are used to locally tune the potential in graphene nanoribbons (GNRs). Here we report on numerical calculations of the quantum capacitance of GNRs using the nextnano software [3] where we solved the two-dimensional Poisson equation and calculated the density in graphene according to Ref. [2]. We investigated several device and potential configurations for nanoribbons with varying width, namely (i) nanoribbons without side gates, (ii) with lateral metal side gates with applied symmetric/antisymmetric potentials, and (iii) with lateral graphene side gates with applied symmetric/antisymmetric potentials. We found that the presence of lateral side gates has significant influence on the capacitance of a graphene nanoribbon.

For studying the electronic properties, and in particular different transport mechanisms in graphene, it is essential to tune the electrostatic potential globally and locally with gate electrodes. This allows, for example, to measure the conductance through a graphene sheet as a function of the Fermi level. Electrostatic coupling between several gate electrodes and graphene has to be calculated numerically. In order to optimally tune transport properties of graphene nanodevices by external parameters, an understanding of different device and gate configurations is necessary. The capacitance of a graphene sheet or a nanoribbon plays a significant role, since it reflects the coupling between the gate potential and the graphene. It also allows to draw a conclusion about the density of states in graphene, and the number of charge carriers which are involved in transport. Here we show numerical calculations of the quantum capacitance of nanoribbons with different gate configurations using the nextnano software [3]. A simple model layout is shown in Fig. 1. It consists of an extended metal back gate (BG), a SiO₂ substrate acting as a dielectric material (εᵣ = 3.9), a graphene nanoribbon of width w and lateral side gates separated by an air spacer of width s. The ideal classical parallel plate capacitance of a 300 nm thick silicon dioxide layer located between two metals is 11.5 nF/cm². Replacing one metal with a graphene layer leads to a slightly smaller capacitance.  

Fig. 1: 2D layout with side gates. The electrostatic potential in the graphene nanoribbon of width w (yellow) is tuned by a metal back gate (red) and by two lateral graphene side gates (yellow) that are separated from the nanoribbon by an air spacer of width s. The density in each graphene region can be tuned separately indicated by the schematic illustration of the three Dirac cones for the case of a symmetric side gate voltage.

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Fig. 2: Capacitance of a graphene nanoribbon (w = 80 nm, s = 30 nm, T = 300 K) with respect to the back gate voltage in the presence of graphene side gates with (I) symmetric and (II) antisymmetric \( (V_{\text{left}} = -V_{\text{right}}) \) voltage, and metallic side gates with (III) symmetric and (IV) antisymmetric side gate voltage. The bias of the graphene nanoribbon is at 0 V.

The capacitance with a dip around the Dirac point where for low back gate voltages the change of density as a function of voltage is smaller due to the low density of states, i.e. due to the quantum capacitance. Graphene nanoribbons (GNRs), however, show a larger capacitance than graphene. The capacitance of nanoribbons without side gates decreases with increasing ribbon width and approaches the limit of an infinite graphene sheet around \( w > 300 \text{ nm} \). For \( w = 30 \text{ nm} \) values of about 80 nF/cm\(^2\) are obtained. For very small GNR widths additional quantum confinement modifies the density of states which is not yet considered in our model but can easily be added [2]. Now we consider two cases: metallic side gates, and graphene side gates. Additionally, we compare a setup for which the same voltage is applied on both (the left and right) side gates (symmetric) with the one where antisymmetric potentials are applied (same absolute value but different in sign) (Fig. 2). We found that nanoribbons with side gates show a smaller capacitance than those without side gates because the side gates partially screen the electric field applied on the back gate. In all cases, the quantum capacitance dip gets broadened for larger side gate voltages. The location of this dip shows the back gate voltage where the Dirac point in the nanoribbon is reached. For symmetric, nonzero side gate potentials, the capacitance is not symmetric any more with respect to \( V_{BG} \) and the dip is shifted away from \( V_{BG} = 0 \text{ V} \). (I) is qualitatively very different from (III) because the graphene side gates exhibit additional quantum capacitance effects. Due to this, graphene side gates feature additional positive peaks (I, II). Furthermore, the dip splits into 2-3 local minima which can be explained by the different positions of the charge neutrality point in the side gates and the nanoribbon (see also the schematic illustration of the Fermi level and the dispersion relation for negative side gate voltages in Fig. 1).

In summary we have shown that the effect of quantum capacitance of a graphene nanoribbon can be differently tuned by either having metal or graphene side gates.

Manipulating light-matter interactions using lithographically defined plasmonic nanostructures

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Metallic nanostructures defined using electron beam lithography on an optically active dielectric open the way to use collective modes of the free electron plasma bound at a metal-dielectric interface (surface plasmon polaritons - SPPs) to guide, confine and manipulate light over length scales far below the diffraction limit. Over the past year, we have been exploring how such lithographically defined metallic nanostructures can be used to manipulate light-matter couplings in hybrid dielectric-plasmonic systems with integrated proximal emitters [1, 2]. The strong local-field enhancements around metallic nanostructures have been shown to strongly influence the strength of light-matter interactions over extreme sub-wavelength dimensions. For example, they can give rise to strong spontaneous emission rate enhancements in hybrid systems that combine metallic nanostructures with proximal emitters and fluorophores [3, 4] and have been predicted to enhance the efficiency of photovoltaic devices [5].

In one study, rectangular SPP Au-waveguides were fabricated on a GaAs substrate including a proximal layer of InGaAs quantum dots (QDs) with an average density of ~100/µm², as depicted schematically in figure 1(a) [1]. The separation between the dots and the surface was 25±2nm, facilitating SPP mediated excitation of QDs [2]. The waveguides are equipped with sub-wavelength scatterers, allowing for the efficient excitation of SPPs. Spatially resolved spectroscopy clearly indicates the presence of unidirectional energy transfer from the propagating SPP modes to the QDs at the far end of the waveguide that are therefore excited via the propagating SPPs. At low excitation levels, sharp line emission from single QDs are observed at the remote end of the waveguide, as identified by their linear emission intensity as a function of excitation power and

![Image](https://via.placeholder.com/150)

Figure 1: (a) Sample layout of a lithographically defined plasmonic waveguide (scanning electron microscope image) on GaAs with near-surface quantum dots (atomic force microscope image). A sub-wavelength scatterer is located at one end of a waveguide enhancing the plasmon generation efficiency. Excitation of quantum dots via propagating plasmons is demonstrated by measuring the QD photoluminescence using a CCD camera. (b) \(g(2)\)-photon correlation function recorded for a single quantum dot. \(g(2)(0)=0.71\) indicates non-classical light emission from a single quantum dot.

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the characteristic spontaneous emission lifetime of $1.1\pm0.2\text{ns}$. Moreover, measurements of the second order autocorrelation function ($g^2(t)$ (figure 1(b)) from single centers reveal antibunched light with $g^2(0)=0.71$, indicative of a SPP excited sub-Poissonian light source. This first result demonstrates the promise to generate non-classical light from sources excited optically over length scales far below the diffraction limit.

In related experiments, lithographically defined Au nanotriangle arrays were fabricated on glass substrates as depicted schematically in figure 2 (a). Ion-implanted CdSe nanocrystals are incorporated into the glass surface as optically active light sources, realized in collaboration with the University of Augsburg [6]. The equilateral triangles have a thickness of 40 nm and are arranged in a square lattice with a periodicity of 300 nm. Varying the base length of the triangles from 100-250 nm enables us to tune the localized surface plasmon resonance (LSPR) from the visible into the infrared regime (600-950 nm) with respect to the CdSe emission. When the LSPR overlaps with the CdSe photoluminescence, as depicted in figure 2 (b), we expect a strong interaction between the plasmonic and the semiconductor system. In this particular case, we obtain an enhancement of the CdSe photoluminescence by a factor of 3x, attributed to the local field enhancement from the localized surface plasmon polaritons in the Au triangle array as shown in figure 2(c). This enhancement arises from a combination of modified spontaneous emission dynamics and a redistribution of the angular emission pattern and could find application in the realization of efficient photon sources or future-type photovoltaic systems with the aim of higher efficiency factors.

In-plane gated field effect transistors based on diamond

Moritz V. Hauf¹, José A. Garrido, and Martin Stutzmann

Diamond shows a variety of extraordinary material properties such as e.g. extreme hardness or a very high thermal conductivity. Although it is considered an insulator with a band-gap of 5.45 eV, diamond can be rendered surface-conductive when the surface is hydrogen-terminated. On the other hand, its insulating properties are restored by oxygen termination of the surface dangling bonds. The ability of locally defining conductive and non-conductive regions on the diamond surface enables the design of in-plane gated field-effect transistors (FET), where the two-dimensional hole gas in the hydrogen terminated diamond surface is laterally depleted [1]. The typical channel width of such transistors is far below 1 µm. These devices are promising candidates in the field of biosensing, where they could be used to detect signals from neurons with high spatial resolution. Furthermore, the concept of in-plane gating can also be applied to charge state control of NV centers in diamond, one of the promising candidates for quantum computing.

![Diagram of in-plane gated diamond FET](image1)

**Fig. 1.** a) Schematic view of an in-plane gated diamond FET with two side gates (G) constraining a conductive channel from source (S) to drain (D). b) Energy bands of a section from one gate across the channel to the other side gate. A gate voltage $\Delta U$ leads to a decrease in the effective channel width $w_{\text{eff}}$.

The typical design of a diamond in-plane gated FET is shown in Figure 1(a). Current can flow through a narrow constriction from source (S) to drain (D) when a voltage $U_{\text{DS}}$ is applied. A gate voltage can be applied to both side gates in order to laterally deplete the conductive channel in the narrowest region. For the fabrication of these devices, high quality single-crystalline diamonds prepared by chemical vapor deposition are used. Surface termination is performed via exposure to oxygen or hydrogen plasma in combination with a surface patterning by photolithography. Electron beam lithography is used for the definition of the gate lines. The conductive hydrogen-terminated regions are contacted by thermal evaporation of Ti and Au.

Figure 1(b) shows the energy bands along a cross section at the narrowest part of the surface-conductive transistor channel. In the hydrogen-terminated gate area, the Fermi level $E_F$ is fixed below the valence band max-

![Graph of transistor characteristics](image2)

**Fig. 2.** Transistor characteristics of in-plane devices with different channel dimensions

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imum $E_V$ due to transfer doping [2]. The oxygen-terminated gate lines present a barrier of roughly 2eV to the holes in the surface conductive gate and channel region. When applying a gate voltage $\Delta U$ between the gate contacts and the channel, a depletion zone is created next to the oxidized lines, shrinking the effective width $w_{\text{eff}}$ of the channel. Figure 2 shows the change of the DC conductance along the channel from source to drain varying with the applied gate voltage. For high positive gate voltages the channel is closed. Starting at a threshold voltage, the channel opens linearly with increasingly negative $U_{\text{GS}}$. The threshold voltage varies between different devices, exhibiting an approximately linear dependence on the channel width. Such a dependence can be understood similar to a two-dimensional depletion at a p-n junction. For negative $U_{\text{GS}}$ the current saturates as the channel width cannot be increased beyond the width defined by the oxygen-terminated gate lines. Overall, the current can be modulated over four orders of magnitude within a relatively small range of $U_{\text{GS}}$.

Low temperature experiments have been performed in a closed-cycle Helium cryostat at $T=2.9$ K. At this temperature, we have observed quantum effects arising from the two-dimensionality of the surface conductive diamond in combination with further lateral, nanometer sized constrictions. Figure 3 shows the AC conductance (at 17 Hz) of the source-drain channel for varying gate and drain-source voltages. Oscillations in the conductance $G$ are observed for constant $U_{\text{DS}}$ which are attributed to Coulomb blockade. The typical diamond shape structures are also observed in Figure 3. The Coulomb blockade requires the presence of a conductive, small island separated from the drain and source via tunneling barriers. For the in-plane gated diamond devices, the origin of such conductive islands is tentatively assigned to potential fluctuations from an imperfect surface termination. With varying gate voltage, the size of the island, the size of the tunneling barriers, and the energy levels of the island are changed. The conductance increases whenever the energy levels lie such that charge carriers can tunnel into and out of the islands. The zero conductance condition (blue area) is met when there is no energy level of the island in the range spanned by the drain and source potential. The observed oscillations are not perfectly regular, which is a fingerprint for the presence of multiple islands connected in series and parallel. In contrast to standard quantum dot systems, the in-plane gates of our devices do not allow a linear shift of the energy levels in the island; instead, the varying gate voltage leads to a change of the island size, changing not only the position of the energy levels but also their spacing.

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Time-resolved ultrafast photocurrents and terahertz generation in freely suspended graphene

Leonhard Prechtel, Li Song, Dieter Schuh, Pulickel Ajayan, Werner Wegscheider, and Alexander W. Holleitner

The high charge-carrier mobility in graphene has spurred a tremendous interest in graphene-based high-speed electronic devices such as field-effect transistors and pn-junctions [1,2]. In combination with its excellent optical properties, graphene further qualifies for optoelectronic applications. Various graphene-based THz-sources and detectors have been proposed, since the frequency of plasma waves, the gap of graphene nanoribbons, and the tunable bandgap in bilayer graphene lies in the THz-range. While the RC-limited bandwidth of graphene-based photodetectors can be estimated to be as large as 640 GHz, common electronic apparatuses cannot resolve the underlying ultrafast charge-carrier dynamics because available equipment cannot produce electronic trigger signals and detect transients faster than tens of picoseconds. We introduce a pump-probe photocurrent spectroscopy in order to resolve their photo-electric response up to 1 THz [3]. In our experiments, we demonstrate that THz-radiation is generated in optically pumped graphene [4]. The electro-magnetic radiation is detected by a coplanar metal stripline, which acts as a highly sensitive near-field antenna and waveguide with a bandwidth of up to 1 THz.

Fig. 1: Ultrafast photocurrent circuitry for graphene. (a) Freely suspended graphene is incorporated into a coplanar stripline circuit. A pump laser pulse focused onto the graphene-sheet generates the time-integrated photocurrent $I_{\text{pd}}$. (b) Spatially resolved scan of $I_{\text{pd}}$. The position of the striplines is indicated with dashed lines ($E_{\text{Laser}} = 1.6$ eV, $P_{\text{Laser}} = 200$ µW, $V_{\text{SD}} = 0$ V, $T_{\text{Bath}} = 300$ K). (c) Single line-sweep of $I_{\text{pd}}$ along the dashed line in Fig. 1b. (d) The time-resolved photocurrent response $I_{\text{sampling}}$ is measured at the field probe, located ~0.3 mm away from the graphene. The probe laser pulse (red circle) triggers the read-out of $I_{\text{sampling}}$.

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Our ultrafast experiments further clarify the optoelectronic mechanisms contributing to the photocurrent generation at graphene-metal interfaces. So far, this photocurrent has been extensively investigated by spatially resolved, but time-integrated photocurrent imaging techniques. We verify that both built-in electric fields, similar to those in semiconductor-metal interfaces, and a photothermoelectric effect give rise to the photocurrent at graphene-metal interfaces at different time scales. Our results open the possibility to design and fabricate graphene-based ultrafast photodetectors, photoswitches, photovoltaic cells, and THz-sources.


Ultrafast photo-thermoelectric and transport currents in GaAs nanowires

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Scanning photocurrent microscopy is a widely used spectroscopy technique to investigate ballistic and diffusive carrier transport and to map the electronic band bending in contacted nanostructures, such as semiconducting nanowires. The photocurrent generation in single semiconducting nanowires has been explained either by carrier drift due to internal and external electric potentials, by carrier diffusion processes, or by a photothermoelectric effect. Recently, numerical simulations highlighted the interplay of the individual contributions of a photothermoelectric current as well as the drift and diffusion of photogenerated electrons and holes in GaAs nanowires \(^1\). However, it has been pointed out that all these optoelectronic effects contribute simultaneously to time-averaging photocurrent measurements, thereby complicating their analysis. Generally, common photocurrent studies are typically limited to time scales exceeding 10 ps because available electronic equipment cannot produce and detect faster trigger signals and transients. Furthermore, optoelectronic charge-carrier dynamics are obscured by the response time of the high-frequency circuits. Yet, it is known from optical experiments that carrier relaxation, thermalization, and recombination processes can occur on much faster time scales in semiconducting nanowires \(^2\).

We therefore apply a recently developed pump–probe photocurrent spectroscopy based on coplanar stripline circuits to investigate the photocurrent dynamics in single p-doped GaAs nanowires with a picosecond time resolution \(^3,4\). We determine the dynamics of the photothermoelectric current, the displacement current, and the transport of photogenerated holes to the electronic contacts as well as the carrier lifetime limited current with unprecedented temporal resolution. In our time-resolved measurements, we are able to separate the individual current contributions because of their characteristic time scales and dynamics in GaAs nanowires. Moreover, we explore the drift velocity of the photogenerated holes \(^5\).

We investigate p-doped GaAs nanowires, which are grown by molecular beam epitaxy (MBE) on a SiO\(_2\)-covered (111)-oriented GaAs substrate (growth rate \(\sim0.25\) Å/s, As\(_4\) partial pressure \(\sim2 \times 10^{-6}\) mbar, growth temperature \(\sim630\) °C, and rotation speed 7 rpm).

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The nanowires with \{110\} facets have a length of 20–30 μm. The diameter of the slightly tapered nanowires increases from \(\sim 80 \text{ nm}\) at the tip to 180 nm at the bottom. The change in diameter is the result of a slight radial growth rate in parallel to the fast axial growth. The nanowires are p-type doped by adding a silicon flux during growth. For these growth conditions, a free hole concentration of \(\sim 2.8 \times 10^{18} \text{ cm}^{-3}\) is estimated at room temperature. The nanowires are mechanically transferred onto a preprocessed sapphire substrate in a random fashion and then contacted in a coplanar stripline circuit by optical lithography (strip width 5 μm, separation 10 μm, metal thickness Ti/Au 10 nm/300 nm). Figure 1a shows an optical microscopy image of such an electrically contacted p-doped GaAs nanowire. As depicted in Figure 1b, a field probe is positioned \(\sim 400 \mu m\) from the nanowire on a \(\sim 200 \text{ nm}\) thick layer of MBE-grown silicon. Our pump/probe approach allows us to experimentally identify and separate the individual photocurrent mechanisms in single p-doped GaAs nanowires (Figure 2), which are overlaid and therefore individually not resolvable in time-integrated scanning photocurrent measurements. We identify a displacement current with a fwhm of \(\sim 1.5 \text{ ps}\) and a photothermal electric current with an exponential decay time of \(\sim 3 \text{ ps}\) [5]. We show that a recombination lifetime limited current with \(\tau_{\text{avg}} = 1510 \pm 30 \text{ ps}\) dominates the time-integrated photocurrent. Finally, we uncover the field-dependent transport velocity of photogenerated holes. Our findings may prove essential for nanowire-based photoswitches, high-speed transistors, photodetectors, and solar cells [5].


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Propagation length of mesoscopic photocurrents in a 2DEG

Markus Stallhofer, Christoph Kastl, Marcel Brändlein, Christoph Karnetzky, Dieter Schuh¹, Werner Wegscheider², G. Abstreiter, J. Kotthaus, and Alexander Holleitner*¹

The electron-electron scattering of quasiparticles with an excess energy above the Fermi energy of a two-dimensional electron gas (2DEG) has been theoretically described by several groups. Such processes preserve the total momentum of the electron system, and in turn, they usually do not contribute directly to the resistance in common transport experiments. In a variety of experiments, Molenkamp and co-workers used one-dimensional quantum point contacts (QPCs) as emitters and detectors for beams of hot electrons and therefore were able to analyze electron-electron scattering and thermoelectric processes in 2DEGs [1]. Related work by Schäpers et al. revealed the temperature dependence of the electron-electron scattering time [2] and for large excess energies, Schinner et al. focused on the additional electron-phonon interaction in such electron beams [3]. Recently, Topinka et al. introduced a scanning gate technique [4] which allows to spatially resolve the electron-electron scattering in such electron beams in close vicinity of a QPC. Although complementary optical experiments highlighted the relaxation and thermalization dynamics of photogenerated hot electrons in 2DEGs [5], none of the above experiments focused on the impact of charge carrier interaction on photoinduced transport currents in 2DEGs.

We present scanning photocurrent measurements performed on low-dimensional electron circuits to explore the average propagation length and hereby the scattering dynamics of photogenerated non-equilibrium charge carriers in a 2DEG. In particular, electron-hole pairs are photogenerated in an AlGaAs/GaAs quantum well comprising a 2DEG, and the resulting current of photogenerated hot electrons in the 2DEG through an adjacent QPC is measured as a function of the laser spot position [Fig. 1(a)]. The QPC acts as an adjustable energy filter for the photogenerated electrons due to its one-dimensional subbands. Therefore, the photocurrent across the QPC shows quantization steps [6,7]. The described optical beam induced current (OBIC) spectroscopy allows us to spatially resolve and energetically analyze the non-equilibrium flow of photogenerated electrons in the low-dimensional electron circuit,

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Fig. 1: (a) Schematic image of a quantum point contact (QPC) with a golden opaque topgate and a 2DEG acting as source and drain contacts. (b) White light interferometric image of the sample. (c) Spatially resolved reflectance of the laser. (d) Optical beam induced current (OBIC) map of the circuit in (c) when left (right) 2DEG section acts as source (drain) contact. (e) OBIC amplitude at position marked with a cross in (d) as a function of $V_G$ for low and high laser intensities. Several quantization steps of the OBIC can be seen (triangles). (f) Dependence of the OBIC (scattered points) on the distance of the excitation spot to the QPC [recorded along the dashed lines in (a), (b), (c), and (d)] for different laser intensities. Scale bars in (b), (c), and (d) are 10 μm.
before the photogenerated electrons and holes recombine with each other (Fig. 1(b)-(e) and [8]). Analyzing the exponential decay of the OBIC amplitude as a function of the distance to the QPC [Fig. 1], we deduce the average propagation length \( \Delta_{\text{decay}} \) of the photogenerated electron ensemble in the 2DEG as a function of the photon energy and laser intensity. For both quasi-resonant and non-resonant photoexcitation of the optical interband transition from the valence to the conduction band in the quantum well, the extracted propagation length of the photocurrent depends non-monotonically on the laser intensity. For low excitation intensities we observe a quasiballistic optoelectronic transport regime in which \( \Delta_{\text{decay}} \) approaches the elastic mean free path of the 2DEG without laser excitation [8]. For intermediate intensities, \( \Delta_{\text{decay}} \) decreases. We interpret the decrease to be caused by an enlarged phase space for individual scattering processes such as electron-electron scattering, as more and more electrons are photogenerated. For the highest laser intensities, \( \Delta_{\text{decay}} \) increases again, which we explain by a Thomas-Fermi screening of momentum scatterers at an overall increased electron density of the 2DEG including the photogenerated electrons. In this regime, the thermalization of the charge carrier ensemble gives rise to an optically induced quasi-Fermi level which dominates the optoelectronic dynamics in the 2DEG. In experiments with a magnetic field applied perpendicularly applied to the 2DEG, we further demonstrate that the electron-electron scattering gives rise to an enlarged magnetic focusing radius of photoinduced ballistic currents compared to the thermalized electrons [9].

Our observations underline the predominant influence of electron-electron scattering and corresponding screening processes on mesoscopic and nanoscale photocurrents [8, 9] and therefore photodetectors.


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Sub-diffraction optical coherent control of ultrafast electrical currents in antenna devices on GaAs

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Conventionally, electrical transport in nanodevices is achieved electronically, i.e., by applying a potential difference to contacts. More recently, also purely optical techniques to induce and control charge transport have been developed. In their most advanced embodiment, a phase-stable superposition of femtosecond fundamental $\omega$ and second harmonic $2\omega$ pulses induces a significant lateral current burst in a semiconductor such as the prototypical material GaAs. Current injection relies on a quantum interference of one- and two-photon absorption [1]. The rate at which currents are injected can be expressed as

$$J \propto E_{\omega}^2 E_{2\omega} \sin(2\phi_\omega - \phi_{2\omega})$$

where $E_{\omega,2\omega}$ are the electric field amplitudes and $\phi_\omega,2\omega$ are the optical phases of the $\omega$ and $2\omega$ light. An appealing aspect of such techniques is that currents can be located wherever one can focus an optical beam. However, achieving current flows confined on nanometer length scales relevant for modern nanoelectronics is hampered by the free-space optics typically used for such coherent control experiments. Recently, we have extended this concept to induce $\mu$A peak currents within the 0.02 $\mu$m$^2$ cross-section of a single GaAs nanowire [2],[3].

Instead of reducing the active optical volume, we here use plasmonic structures with their characteristic subwavelength field confinement in an alternative approach to achieve sub-diffraction control of currents [4]. The most straightforward approach for localized field enhancements relies on optical antennas. Such devices are nowadays routinely used to deliberately convert the energy of propagating free-space radiation into localized energy. Optical antennas hold promise for applications in areas such as light-emitting devices, photovoltaics, and spectroscopy. Closely related to the antenna-mediated field enhancement, also many nonlinear optical interactions are found to be massively enhanced. However, the potential of antennas to optimize current injection into

Fig. 1: (a) Photocurrent $I_{PHOTO}$ through the metal-LT-GaAs-metal device for various relative phases $\Delta \phi = \phi_\omega - \phi_{2\omega}$ between the $\omega$ and $2\omega$ frequency components. The amplitude of the sinusoidal fit (solid line) reveals the magnitude of the coherently controlled photocurrent. (b) Scanning electron microscope (SEM) image of a gold nanoantenna defined at the center of a 15 $\mu$m wide LT-GaAs bar. (c) Schematic of the sample and the measurement circuit (not to scale).

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sub-diffraction semiconductor specimen remains unexplored to date. In this letter, we
close this gap and consider current injection in GaAs material functionalized with optical
antennas. GaAs is a convenient prototypical semiconductor where currents can be in-
duced with telecom radiation at 1.55 μm and its second harmonic. The main focus of this
study is the comparative analysis of different optical antennas in view of an enhancement
of the nonlinear optical current injection. Most importantly, we clearly identify current
enhancements related to plasmonic functionalities of bow tie gold antennas on a semi-
conducting GaAs substrate [4].

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251119 (2012)
Biophysics and Bioelectronics
Photocurrent of a single photosynthetic protein

Daniel Gerster¹, Joachim Reichert¹, Hai Bi¹, Johannes Barth¹, Iris Visoly-Fisher², Shlomi Sergani², Itai Carmeli³, Simone Kaniber and Alexander Holleitner*

Photosynthesis is used by plants, algae and bacteria to convert solar energy into stable chemical energy. The initial stages of this process - where light is absorbed and energy and electrons are transferred - are mediated by reaction centres composed of chlorophyll and carotenoid complexes [1]. It has been previously shown that single small molecules can be used as functional components in electric and optoelectronic circuits, but it has proved difficult to control and probe individual molecules for photovoltaic and photoelectrochemical applications. We show that the photocurrent generated by a single photosynthetic protein – the photosystem I (PS I) - can be measured using a scanning near-field optical microscope set-up [2]. One side of the protein is anchored to a gold surface that acts as an electrode, and the other is contacted by a gold-covered glass tip. The tip functions as both counter electrode and light source. A photocurrent of 10 pA is recorded from the covalently bound single-protein junctions, which is in agreement with the internal electron transfer times of the PS I.

In our set-up, the PS I was covalently bound to the substrate and a metallized scanning near-field optical microscopy (SNOM) tip via cysteine mutation groups (Fig. 1). Photoexcitation of PS I triggers a series of redox reactions in which an electron is transferred along the reaction-centre electron transfer chain with an internal quantum efficiency close to 1 [1]. We used bipolar mutants of PS I, where the mutations are located at both the oxidizing and reducing sides of the PS I [3],[4],[5]. The cysteine groups promote an oriented self-assembly of the PS I on surfaces as well as good electronic coupling between the PS I and the electrodes. For control measurements, we utilized unipolar mutants of PS I with two cysteine groups only on the oxidizing side. The unipolar PS I has no cysteine mutation on the reducing side of the electron pathway.

Generally, the PS I complex consists of 12 polypeptides, to which 96 light-harvesting chlorophyll and 22 carotenoid pigment molecules are bound [1]. The PS I protein has a

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cylindrical shape with a diameter of ~15 nm and a height of 9 nm. After photoexcitation of the special pair of chlorophyll (P700) an electron is transferred to a monomeric chlorophyll. The excited electron relaxes via two intermediate phylloquinones to three [4Fe–4S] iron-sulphur centres. The first iron cluster (FX) is located just outside the molecular electron transfer chain, and the transfer rate from the phylloquinones to FX is biphasic with time constants of ~15–150 ns. The electron is then transferred to the last two iron clusters FA/B in less than 500 ns.

One of the most significant results in our experiment is an intriguingly large value of ~10 pA for the measured photocurrent. This translates into a turnover time of ~16 ns. In other words, a photoexcited electron transverses the PS I covalently bound between the two electrodes every ~16 ns. At the same time, a photoexcited electron reaches FX in ~15 ns at the earliest, equivalent to the rate we deduce from our photocurrent measurements. Therefore, the expected limiting step of the electron transfer - electron transfer from FX to FA/B – seems to be overcome by a direct transfer process to the covalently bound tip [2].

Our results demonstrate that individual PS I units can be integrated and selectively addressed in nanoscale photovoltaic devices while retaining their biomolecular functional properties. They act as light-driven, highly efficient single-molecule electron pumps that can function as current generators in nanoscale electric circuits [2].

Synthetic lipid membrane channels formed by designed DNA nanostructures

Martin Langecker¹, Vera Arnault¹, Thomas G. Martin², Jonathan List¹, Stephan Renner¹, Michael Mayer³, Hendrik Dietz⁵, and Friedrich C. Simmel⁶†

We report on a synthetic membrane channel that is constructed entirely from DNA and anchored to a lipid membrane with cholesterol side chains. Scaffolded DNA origami was used to create a synthetic membrane channel that consists of a hollow stem that penetrates and spans a lipid bilayer membrane, and a barrel-shaped cap that adheres to the membrane via cholesterol moieties [1].

![Fig. 1: Synthetic DNA membrane channels. (A) Schematic illustration of the channel formed by 54 double-helical DNA domains packed on a honeycomb lattice. Cylinders indicate double-helical DNA domains. Red denotes transmembrane stem; orange strands with orange ellipsoids indicate cholesterol-modified oligonucleotides that hybridize to single-stranded DNA adaptor strands. (B) Averaged negative-stain TEM images obtained from purified DNA channel structures. (C and D) Example TEM images of DNA channels adhering to small unilamellar vesicles (SUVs) made from POPC lipids.](image)

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Transmission electron microscopy (TEM) was used to confirm that the intended shape is realized and shows binding of the synthetic DNA channels to lipid bilayer membranes in the desired orientation (see Fig. 1).

The conductance of the resulting membrane pores was studied by means of single-channel electrophysiological experiments (see Fig. 2). Successful membrane incorporation of individual synthetic DNA channels manifested itself in a stepwise increase in transmembrane current along with an increase in electrical noise. The synthetic DNA channels displayed an average Ohmic conductance of 0.87 nS per channel (in 1 M KCl solution), which agrees favorably with expectations based on the channel geometry.

Similar to naturally occurring ion channels, the synthetic DNA channels also displayed gating behavior, which may be caused by thermal fluctuations of the structure. More pronounced gating was seen for mutations in which a single DNA strand of the stem protruded into the channel.

Geometry and chemical properties of synthetic DNA channels can be tailored for custom nanopore sensing applications. We also show that synthetic DNA channels can be used for single molecule studies of DNA secondary structures.

Synthetic DNA channels introduced here open up broad perspectives for further applications as antimicrobial agents and interference with cellular homeostasis. We believe that fully synthetic lipid membrane channels are a first step towards harnessing ion flux for driving sophisticated nanodevices that are inspired by the functional diversity of natural membrane machines such as ion pumps, rotary motors, and transport proteins.

Photocurrent in diamond-based biohybrid systems for energy harvesting applications

Roberta Caterino¹, Matthias Sachsenhauser, Michael Metzger, Martin Stutzmann, and Jose A. Garrido

Photosynthetic reaction centers (RCs) are protein complexes responsible for solar energy harvesting in plants, algae, and bacteria. The high efficiency of these species in achieving charge separation under photo-stimulation has attracted interest in using RCs as a functional unit in bio-solar cells. However, the complexity of the charge transfer between these biological species and the inorganic electrode typically leads to low values of the measured photocurrents in such systems.

Great effort has been devoted in the last years to optimize the immobilization of RCs on several surfaces making use of suitable linker molecules [1].

Diamond electrodes have attracted considerable attention for their use in applications requiring stable operation in harsh conditions or a large electrochemical potential window. In this work, we explore the use of diamond electrodes in hybrid systems for energy harvesting. For this application, the electrode material is expected to offer a convenient surface to immobilize organic redox groups, proteins or enzymes, and to exhibit an efficient charge transfer to them.

Metal electrodes, and in particular Au electrodes have been shown to exhibit a fast charge transfer in electrolyte environment, but at the same time they are not able to form stable bonds with organic and bioorganic molecules. Diamond electrodes, in contrast, offer a suitable surface for chemical modification, due to the carbon chemistry versatility and to the possibility of covalently immobilizing a monolayer of linker molecules. This work demonstrates recent progress in the use of diamond electrodes in bio-hybrid systems for solar energy harvesting.

Figure 1 shows a schematic view of the hybrid system, in which a highly conductive B-doped diamond substrate is modified according to several functionalization routes, aiming at introducing diverse functional self-assembled monolayers (SAM) on it. Carboxyl-terminated linker molecules have been activated and exploited to tether cytochrome C

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to the electrode’s surface. Finally, the RCs have been physisorbed on the modified electrode and characterized in a standard three-electrode photo-electrochemical cell, containing the enzyme $Q_0$ in a buffer solution.

We have found that the role of cytochrome C and $Q_0$ in the charge transfer process is similar to the role they play in the natural environment of RCs, with cytochrome C shuttling the low-energy electrons from the electrode to the RCs P-side and $Q_0$ extracting the high energy electron from the Q-side of the RCs and shuttling it into the electrolytic solution. A schematic diagram of the energy levels on the right side of Fig 1, shows the direction of the charge transfer in the hybrid system that generates a cathodic photocurrent.

In Fig 2a) we report the recorded photocurrent density during time intervals of 300 seconds, with alternating light on and off. The plot shows a fast response upon photo-stimulation and then a photocurrent decay that is tentatively attributed to the limited-efficiency of $Q_0$ in extracting the high energy electron from the RCs and carrying it to the counter electrode through diffusion of its reduced species $QH_2$. The recorded signal is fairly stable over time and it is possible to reach comparable levels of absolute photocurrent density after measuring for several hours.

A deeper insight into these processes can be achieved by studying the photocurrent signal as a function of the position of Fermi level in diamond. In Fig 2b) the value of the photocurrent density after 300s of exposure to light is plotted as a function of the voltage applied between reference and working electrode. The observed increase of photocurrent at more negative voltages can be understood by considering the effect of the overpotential with respect to the formal potential of cytochrome C, which is around 0 V. Eventually, the photocurrent decreases for voltages more negative than -200 mV; at this potential, a competing electron transfer related to the $QH_2/Q_0$ redox couple sets in at the diamond electrode.

A model able to explain the photocurrent behavior for the whole range of applied voltage will be the subject of a further study. With it, we aim at gaining a deeper understanding of the different steps involved in the charge transfer induced by photo-excitation and to clarify how the energetic level of electrodes and redox species can be tuned to maximize the measured photocurrent levels.

Fig. 2: a) Photocurrent density recorded applying a voltage of -100 mV on the working electrode and alternating intervals of 300s of exposure to IR-LED illumination to 300s of dark. b)Values of photocurrent density recorded after 300s exposure to IR-LED illumination as a function of applied voltage to the electrode.


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Graphene transistors for sensing in electrolytic environments

Benno Blaschke, Lucas H. Hess¹, Frank Deubel², Jose A. Garrido

The development of the future generation of neuroprosthetic devices will require the advancement of novel solid-state sensors and actuators with a further improvement in the signal detection capability, a superior stability in biological environments, and a more suitable compatibility with living tissue. To date, interfacing of living cells and tissue with solid-state electronic devices has mainly been based on conventional silicon technology, in particular using Si metal-oxide-semiconductor field-effect transistor (MOSFET) structures. However, some of the drawbacks associated with this technology, such as its limited stability in aqueous environments and a relatively high electrical noise, have triggered the study of alternative materials and technologies. In this respect, solution-gated field-effect transistors (SGFETs) based on Si-nanowires, AlGaN/GaN heterostructures, H-terminated diamond, carbon nanotubes, and, more recently, graphene have been investigated as sensing devices. Among these materials, graphene is a particularly attractive candidate for bioelectronic applications, due to its remarkable physical and chemical properties. The extremely high charge carrier mobility in graphene leads to a field-effect transistor (FET) performance that is superior to most known semiconductors.

Recently, the performance of graphene solution-gated field-effect transistors fabricated on different substrates was investigated using a new setup that allows the simultaneous characterization of 32 transistors in an electrolyte. The transistor characterization, and in particular the position of the Dirac voltage, reveals a similar p-type doping for devices prepared on silicon dioxide, silicon nitride and sapphire substrates. The variation of the doping level between different transistors on the same substrate has been tentatively attributed to surface contamination of graphene originating from the fabrication process. In the same manner, the transconductance of the transistors is strongly influenced by contamination (e.g. photoresist, residual salts) and device degradation, whereas the substrate type does not seem to play an important role. Furthermore, the pH sensitivity of the graphene SGFETs shows a qualitatively similar behavior for all investigated substrates. A simple model, assuming the presence of acidic groups at the gra-

Fig. 1: Transfer curves of graphene SGFETs on two different substrates. The measurements on each side were performed simultaneously. A similar p-type doping is observed for several substrates including sapphire, silicon dioxide and silicon nitride (not shown).

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Graphene/electrolyte interface with pKa = 4.5, can be used to explain the obtained pH sensitivities, having values from 13 mV/dec to 40 mV/dec in the range between pH 3 and pH 7. Graphene devices on all substrates are pH insensitive for pH greater than 7. The exact origin and nature of the acidic surface groups could not be determined yet. The experimental results, however, suggest a dominant role of defect groups located in the graphene layer or acidic groups related to surface contamination. Substrate surface groups seem to have little influence on the pH sensitivity. In addition, the sensitivity of graphene SGFETs to monovalent and divalent ions has been investigated and a model was developed to quantify the experimental data [1]. This model considers screening of a pH-dependent surface charge at the graphene/electrolyte interface by ions in the solution and is in excellent agreement with the results for both mono- and divalent salts. Possibly, the surface charge originates from charged acidic groups or charged contaminants. It was found that the screening effect is dominated by the cations (anions) if the surface charge is negative (positive). The ion sensitivity of the transistors depends only on the surface charge of the transistors and seems to be independent of the substrate. The observed similar ion sensitivity to different monovalent ions indicates the absence of specific adsorption. Furthermore, graphene SGFETs have been modified with copolymer brushes of styrene and dimethylaminoethyl methacrylate (DMAEMA) [2]. The polymer brushes cause an n-type doping of the graphene. In addition, the polymer brushes change the pH sensitivity range and increase the pH sensitivity of the transistors. Furthermore, the ion sensitivity of the polymer brush covered sample suggests the presence of a positive surface charge, which is in agreement with the observed n-type doping.

We have analyzed the sensitivity of graphene SGFETs to the electrolyte’s pH and ion content experimentally and compared it to a numeric model in order to determine the origin of this sensitivity. Moreover, it has been demonstrated that the pH sensitivity of graphene transistors can be modified by introducing additional functional groups via surface polymerization.

Fig. 2: pH sensitivity of graphene SGFETs. (a) Unmodified graphene SGFETs exhibit a pH sensitivity in the lower pH region that is attributed to a surface group with pKa 4.5. (b) An additional sensitivity can be obtained by the growth of styrene-DMAEMA copolymer brushes on graphene due to the pKa of 7.5 of the DMAEMA group.

This work was supported by the German Research Foundation (DFG) in the framework of the Priority Program 1459 “Graphene”, the European Union through the project “NeuroCare” and the Nanosystems Initiative Munich (NIM).

Distance dependence of single-fluorophore quenching by Gold nanoparticles studied on DNA origami


We use self-assembled DNA structures (DNA origami) as a breadboard to precisely attach a fluorophore and a 10nm metallic nanoparticle. With that strategy we achieve an outstanding control over structure and stoichiometry and the ability to study the distance-dependent quenching of fluorescence due to a metallic nanoparticle; in order to get this dependency fluorescence lifetime imaging is used. Our findings are in good agreement with exact calculations that include dipole-dipole orientations and distances. The resulting characteristic distance of 50% energy transfer is 10.4nm when a more practical model is used [1].


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DNA-based self-assembly of chiral plasmonic nanostructures with tailored optical response


Gold nanoparticles can be used for constructions on the length-scale comparable to the wavelength of light or even smaller; regarding this their surface plasmon resonances and hence interaction with light are tailored by structural alterations. Here lithographic methods are not practical, because they are limited in resolution and their ability to create three-dimensional structures. DNA-origami provide an optional route to fabricate controlled arrangements in complex and also chiral geometries of nanoparticles by DNA self-assembly.

We demonstrated [1] how gold nanoparticles and DNA-origami are used to build nanometer-scale helices that exhibit defined circular dicroism and optical rotatory dispersion effects at visible wavelength. These findings originate from the collective plasmon-plasmon interactions of nanoparticles, which are positioned with a precision of two nanometers. Further on our nanoparticle assemblies are tunable in handedness, color and intensity with good agreement with our theoretical model.

Fig: (a) Left- and right-handed nanohelices formed by nine gold nanoparticles that are attached to the surface of DNA origami 25-helix bundles. Each nanoparticle is fixed by three 15-nucleotide-long single-stranded oligonucleotides, which hybridize with complementary thiol-modified DNA strands bound to the nanoparticles. (b) TEM image of assembled gold nanohelices. The directed attachment yields in a success of 98%.


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3. **Research Funding and Collaborations**

Many of our research projects have benefited from very fruitful collaborations with external groups either via joint projects, individual collaborations, exchange programs, or through direct interaction with visitors. The major external collaborations are based on joint projects which are financially supported by different organizations. The total amount of external funding exceeded again 3 Mio € in 2012.

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   - Verbundprojekt QK_QualH-Rep: Quantenrepeater-Plattformen auf Basis von Halbleitern, TP: Integrierte quanten-photonische Schaltkreise
   - GO-Bio 4: Dynamic Biosensors: Gründungsvorhaben zur Kommerzialisierung der switchSENSE Technologie, einer Chip-basierten Plattform zur effizienten Analyse von Proteinen

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   - Verbundprojekt in Bayern: Solar Technologies go Hybrid: Organische und hybride Materialsysteme für solare Technologien der nächsten Generation

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   - Schwerpunktprogramm: Neue Methoden der EPR-Spektroskopie
   - Schwerpunktprogramm: Nanostrukturierte Thermoelektrika
   - Sonderforschungsbereich: Kräfte in biomolekularen Systemen (SFB 863)
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   - AB 35/10-1: Sub – 10 nm – Nanotransfer - Drucktechnik auf der Grundlage von MBE-Stempeln für neuartige Anwendungen in der organischen und molekularen Elektronik
   - BR 1585/5-1: Quantum properties of dopants for silicon nanospintronics
   - BR 1585/6-1: Nanostrukturierte Thermoelektrika: Modellsysteme und kontrollierte Synthese
   - BR 1585/6-2: Nanostrukturierte Thermoelektrika: Theorie, Modellsysteme und kontrollierte Synthese
   - BR 1585/7-1: Electrical control and read-out of color centers in diamonds
• BR 1585/8-1: Neue Konzepte für gepulste elektrisch detektierte magnetische Resonanz mit hoher Nachweisempfindlichkeit
• GA 1432/1-1: Functionalization of diamond surfaces for biosensor applications
• GA 1432/2-1: SPP Graphene: Graphene solution-gate field effect transistors for biosensor applications
• HO 3324/4-2: Optically induced non-equilibrium spin transport in mesoscopic semiconductor circuits
• HO 3324/4-3: Optically induced non-equilibrium spin transport in mesoscopic semiconductor circuits
• KO 4005/2-1: InAs-based nanowires on silicon platform for novel nanoscale high electron mobility heterojunction devices
• SH 548/1-1: SPP Graphene: Graphene solution-gate field effect transistors for biosensor applications
• VO 483/5-2: Microscopic theory of spin-splittings and ballistic spin currents in semiconductor

4. Excellence Initiative of Federal and State Governments
   • Cluster of Excellence Nanosystems Initiative Munich
   • TUM International Graduate School of Science and Engineering (IGSSE)
   • TUM Institute for Advanced Study (IAS)
   • Cluster of Excellence: Center for Protein Science Munich (CIPSM)

5. Euromed Alliance
   • ISPV: Interface science for photovoltaics

6. Bayerisch-Kalifornisches Hochschulzentrum – BaCaTeC
   • Scanning force microscopy on hydrogen terminated diamond surfaces
   • Atomic scale composition, dopant and interface segregation analysis of single semiconductor nanowires by laser-induced atom probe tomography
   • Semiconductor integrated quantum optical circuits

7. DAAD
   • Partnerschaft mit Australien

8. Alexander von Humboldt-Stiftung
   • Humboldt-Forschungsstipendium: Hua Li

9. Graduiertenförderung
   • Elitenetzwerk Bayern
   • International Graduate School: Materials Science of Complex Interfaces (CompInt)

10. European Union
    • Marie Curie FP7 Peoples – International Reintegration Grant (IRG): Self-assembled growth of III–V semiconductor nanowires on Si for future photonic and high electron mobility applications
    • MATCON: Materials and interfaces for energy conversion and storage
- NanoPV: Nanomaterials and nanotechnology for advanced photovoltaics
- NeuroCare: Neuronal NanoCarbon Interfacing Structures
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- Marie Curie IEF: Solid-state quantum optical devices (SQOD)
- Marie Curie: S3Nano - Few spin solid-state nano-systems
- SOLID: Solid state systems for quantum information processing
- NanoREAL (Real-time nanoscale optoelectronics) ERC
- HYSENS (Hybrid Molecule-Nanocrystal Assemblies for Photonic and Electronic Sensing Applications)

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- MISTI, bilateral project with MIT: Investigation of noise of graphene transistors

13. Industry
- Evonik Degussa GmbH, Marl, Germany: NADNuM
- Fujitsu Laboratories Ltd.: SwitchDNA Biosensor
- IPB mbH & Co. KG, Schönefeld, Germany: Polykristalline Si-Dünnschichten
- Rohde & Schwarz, München, Germany: Zero-Bias Schottky-Dioden
-.Vertilas, Garching, Germany: Langwellige VCSEL
- Infineon Technologies, München, Germany: Elektronen-Spin-Resonanz von Donatoren
### International collaborations

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<td>Martyn Amos</td>
<td>Manchester Metropolitan University, Manchester, UK</td>
<td>Synthetic biology</td>
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<tr>
<td>Yasuhiko Arakawa</td>
<td>University of Tokyo, Japan</td>
<td>Optical spectroscopy of quantum dots</td>
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<td>Commissariat à l’Energie Atomique, Saclay, France</td>
<td>Neurons on diamond surfaces</td>
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<tr>
<td>Michel Calame</td>
<td>Universität Basel, Switzerland</td>
<td>Optoelectronics of nanoparticle arrays</td>
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<tr>
<td>Itai Carmeli</td>
<td>Tel Aviv University, Israel</td>
<td>Photosynthetic proteins</td>
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<tr>
<td>Yves Chabal</td>
<td>Rutgers University, Piscataway, USA</td>
<td>FTIR studies of hydrogen-induced exfoliation of Ge</td>
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<tr>
<td>Connie Chang-Hasnain</td>
<td>University of California, Berkeley, USA</td>
<td>Subwavelength gratings, long-wavelength VCSELs</td>
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<tr>
<td>Lukas Chrostowski</td>
<td>University of British Columbia, Vancouver, Canada</td>
<td>Tunable VCSELs</td>
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<tr>
<td>Pierluigi Debernardi</td>
<td>Consiglio Nazionale della Ricerche, IEIIT-CNR, Torino, Italy</td>
<td>Simulation of tunable VCSELs</td>
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<tr>
<td>Klaus Ensslin</td>
<td>ETH Zürich, Switzerland</td>
<td>Transport through quantum dots</td>
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<tr>
<td>John Foord</td>
<td>University of Oxford, UK</td>
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<tr>
<td>Stephen Goodnick</td>
<td>Arizona State University, Phoenix, USA</td>
<td>Applications of novel density functional methods</td>
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<tr>
<td>Sasha Govorov</td>
<td>Ohio University, Athens, USA</td>
<td>Exciton traps</td>
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<tr>
<td>Ken Haenen</td>
<td>Interuniversitair Micro-Electronic Centrum, Hasselt, Belgium</td>
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<tr>
<td>Eugene E. Haller</td>
<td>University of California, Berkeley, USA</td>
<td>Isotopical engineering of Si and Ge</td>
</tr>
<tr>
<td>Daniela Iacopina</td>
<td>Tyndall National Institute, Cork, Ireland</td>
<td>Nanoparticle optoelectronics</td>
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<tr>
<td>Kohei M. Itoh</td>
<td>Keio University, Yokohama, Japan</td>
<td>Isotopical engineering of Si and Ge</td>
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<tr>
<td>Richard Jackman</td>
<td>University of College London, London, UK</td>
<td>Diamond biosensors</td>
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<tr>
<td>Klaus Kern</td>
<td>Max-Planck-Institut, Stuttgart</td>
<td>Topological Insulators</td>
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<tr>
<td>Paul Koenraad</td>
<td>Technical University of Eindhoven, The Netherlands</td>
<td>Scanning tunnelling microscopy of coupled quantum dot nanostructures</td>
</tr>
<tr>
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<tr>
<td>Sigmund Kohler</td>
<td>Instituto de Ciencia de Materiales de Madrid, CSIC, Spain</td>
<td>Ballistic photocurrents in mesoscopic structures</td>
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<tr>
<td>Philomela Komninou</td>
<td>Aristotle University of Thessaloniki, Greece</td>
<td>DOTSENSE</td>
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<tr>
<td>Frank Koppens</td>
<td>The Institute of Photonic Science, Barcelona, Spain</td>
<td>Graphene-based optoelectronics</td>
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<tr>
<td>Anders Larsson</td>
<td>Chalmers University, Gothenburg, Sweden</td>
<td>Modelling of VCSEls</td>
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<tr>
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<tr>
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<td>Universidad Autónoma de Madrid, Spain</td>
<td>Physics of light matter interactions</td>
</tr>
<tr>
<td>Shuit-Tong Lee</td>
<td>Institute of Functional Nano &amp; Soft Materials, Soochow University, Su Zhou, China</td>
<td>TUM IAS</td>
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<tr>
<td>Song Li</td>
<td>Shinshu University, Nagano-shi, Japan</td>
<td>Graphene, CNTs growth</td>
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<tr>
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<td>Topological insulatas, China</td>
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<tr>
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<td>National University of Singapore, Singapore</td>
<td>Graphene</td>
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<tr>
<td>Daniel Loss</td>
<td>University of Basel, Switzerland</td>
<td>Theory of carrier spin relaxation in QDs</td>
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<tr>
<td>Hideyuki Maki</td>
<td>Keio University, Tokio, Japan</td>
<td>CNT optoelectronics</td>
</tr>
<tr>
<td>Marcus Mangold</td>
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<td>Nanoparticle arrays</td>
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<tr>
<td>Marcel Mayor</td>
<td>University of Basel, Basel, Switzerland</td>
<td>Molecular electronics</td>
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<tr>
<td>Eva Monroy</td>
<td>Commissariat à l’Energie Atomique, Grenoble, France</td>
<td>III-nitride quantum dots</td>
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<tr>
<td>Joan Ramon Morante Jordi Arbiol</td>
<td>Universitat de Barcelona, Spain</td>
<td>III-nitride and metal-oxide nanostructures</td>
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<tr>
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<td>High resolution transmission electron microscopy of nanowires</td>
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<tr>
<td>Elias Munoz</td>
<td>Universidad Politécnica de Madrid, Madrid, Spain</td>
<td>Noise characterization of diamond transistors</td>
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<tr>
<td>Roberto Myers</td>
<td>Ohio State University, USA</td>
<td>Nanowire based optoelectronics</td>
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<tr>
<td>Milos Nesladek</td>
<td>University Hasselt, Belgium</td>
<td>Neurons on diamond surfaces</td>
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<tr>
<td>Tomas Palacios</td>
<td>MIT, Boston, USA</td>
<td>Graphene bioelectronics</td>
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<tr>
<td>Rui Pereira</td>
<td>University of Aveiro, Portugal</td>
<td>Doping of nanocrystals</td>
</tr>
<tr>
<td>Serge Picaud</td>
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<td>Retina cells on diamond surfaces</td>
</tr>
<tr>
<td>Jaromir Rehak Ales Poruba</td>
<td>Solartec, Radhostern Roznov Pod Radhostern, Czech Republic</td>
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<tr>
<td>Heike Riel</td>
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</tr>
<tr>
<td>Name</td>
<td>Institution/Company</td>
<td>Research Focus</td>
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<tr>
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<tr>
<td>Daniele Sanvitto</td>
<td>NNL, Instituto Nanoscienze, CNR Lecce, Italy</td>
<td>Cavity QED physics using semiconductors</td>
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<tr>
<td>Ian Sharp</td>
<td>Joint Center for Artificial Photosynthesis, Berkeley, USA</td>
<td>Surface functionalization of semiconductors</td>
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<tr>
<td>Michelle Simmons</td>
<td>University of New South Wales, Australia</td>
<td>Single donor devices</td>
</tr>
<tr>
<td>Doris Steinmüller-Nethl</td>
<td>Rho-BeSt Hartstoff-beschichtungs GmbH, Innsbruck, Austria</td>
<td>MATCON</td>
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<tr>
<td>Sasha Tartakovskii</td>
<td>University of Sheffield, Sheffield, UK</td>
<td>Nuclear spin phenomena in InGaAs-GaAs quantum dots</td>
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<tr>
<td>Mike Thewalt</td>
<td>Simon Fraser University, Canada</td>
<td>Isotope engineering of Si and Ge</td>
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<tr>
<td>Karl Unterrainer</td>
<td>Technische Universität Wien, Austria</td>
<td>Quantum cascade laser</td>
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<tr>
<td>Milan Vanecek</td>
<td>Fyzikalni ustav, Prague, Czech Republic</td>
<td>Optical characterization of diamond films</td>
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<tr>
<td>José Villas-Boas</td>
<td>Instituto de Fisica, Universidade Federal de Uberlandia, Uberlandia MG, Brazil</td>
<td>Theory of cavity QED effects in PC-nanostructures</td>
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<tr>
<td>Jelena Vuckovic</td>
<td>Stanford University, CA, USA</td>
<td>Quantum non-linear optics</td>
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<tr>
<td>Elaine Wong</td>
<td>University of Melbourne, Australia</td>
<td>High speed data transmitting systems</td>
</tr>
<tr>
<td>Naoki Yokoyama, Shozo Fujita</td>
<td>Fujitsu Laboratories Ltd, Atsugi, Japan</td>
<td>Protein sensors</td>
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### National collaborations

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<tr>
<td>Manfred Bayer</td>
<td>Universität Dortmund</td>
<td>Spin phenomena in quantum dot nanostructures</td>
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<tr>
<td>Markus Betz</td>
<td>Technische Universität Dortmund</td>
<td>Coherent control of photocurrents</td>
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<tr>
<td>Dominique Bougeard</td>
<td>Universität Regensburg</td>
<td>Si/SiGe based systems</td>
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<tr>
<td>Reinhard Carius, Friedhelm Finger, Martina Luynsberg, Gustav Bihlmayer</td>
<td>Forschungszentrum Jülich</td>
<td>Amorphous thin films</td>
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<tr>
<td>Martin Eickhoff</td>
<td>Justus-Liebig-Universität Gießen</td>
<td>DOTSENSE</td>
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<tr>
<td>Peter Feulner</td>
<td>Technische Universität München</td>
<td>Surface and interface analysis</td>
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<tr>
<td>Roland Fischer</td>
<td>Universität Bochum</td>
<td>NADNuM</td>
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<tr>
<td>Maximilian Fleischer</td>
<td>Siemens AG, München</td>
<td>Antibody immobilization on GaN VCSEL-based optical sensors</td>
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<tr>
<td>Alois Friedberger</td>
<td>EADS Deutschland GmbH, München</td>
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<tr>
<td>Uwe Gerstmann</td>
<td>Universität Paderborn</td>
<td>Hyperfine interactions</td>
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<tr>
<td>Hermann Gaub</td>
<td>Ludwig-Maximilians-Universität München</td>
<td>Nanofabrication</td>
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<tr>
<td>Peter Hänggi</td>
<td>Universität Augsburg</td>
<td>Ballistic photocurrents in mesoscopic structures</td>
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<td>Thorsten Hugel</td>
<td>Technische Universität München</td>
<td>Nanotribology</td>
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<td>Rainer Jordan</td>
<td>Technische Universität Dresden</td>
<td>Polymer brushes on semiconductors</td>
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<tr>
<td>Khaled Karrai</td>
<td>attocube, München</td>
<td>Transmission experiments on quantum dots</td>
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<tr>
<td>Klaus von Klitzing, Jürgen Smet, Werner Dietsche</td>
<td>MPI für Festkörperforschung, Stuttgart</td>
<td>Coupled 2d systems, quantum Hall systems</td>
</tr>
<tr>
<td>Jörg Peter Kotthaus</td>
<td>Ludwig-Maximilians-Universität München, CeNS, München</td>
<td>GaAs based hetero- and nanostructures, simulation of gated quantum dots</td>
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<tr>
<td>Hubert Krenner</td>
<td>Universität Augsburg</td>
<td>Control of quantum states using surface acoustic waves</td>
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<tr>
<td>Klaus Lips</td>
<td>Helmholtz-Zentrum Berlin</td>
<td>Staebler-Wronski-Effekt</td>
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<tr>
<td>Paolo Lugli</td>
<td>Technische Universität München</td>
<td>Nano-imprint lithography of SOI photonic nanostructures</td>
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<tr>
<td>Peter Meissner</td>
<td>Technische Universität Darmstadt</td>
<td>Widely tunable MEMS-VCSEL</td>
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<td>Bruno K. Meyer</td>
<td>Justus-Liebig-Universität Gießen</td>
<td>Spektroskopie von ZnMgO</td>
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<tr>
<td>Gerhard Müller</td>
<td>EADS Deutschland GmbH, München</td>
<td>Nano-optical chemical transducers</td>
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<td>Christoph Nebel</td>
<td>Fraunhofer-Institut für Angewandte Festkörperphysik, Freiburg</td>
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<td>Bert Nickel</td>
<td>Ludwig-Maximilians-Universität München</td>
<td>Diamond/pentacene heterostructures SAMs on GaN</td>
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<td>Andreas Offenhaeusser</td>
<td>Forschungszentrum Jülich</td>
<td>Neurons on diamond ISFETs, cells on AlGaN/GaN FETs</td>
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<td>Hans Hübl, Matthias Opel, Rudolf Gross, Sebastian Gönnenwein</td>
<td>Walther-Meissner-Institut, Garching</td>
<td>Magnetic resonance</td>
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<td>Markus Ortsiefer</td>
<td>VERTILAS Gmbh, Garching</td>
<td>InP-based VCSEL</td>
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<td>Thomas Reichel</td>
<td>Rohde &amp; Schwarz, München</td>
<td>Microwave monolithically integrated circuits (MMIC) Zero-bias Schottky diodes</td>
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<td>Joachim Reichert</td>
<td>Technische Universität München</td>
<td>Optoelectronics in photosynthetic protein structures</td>
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<td>Roland Schmeckel, Hasso Wolf, Gabi Schirning</td>
<td>Universität Duisburg-Essen</td>
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<td>Ulrich Schmid, Helmut Seidel</td>
<td>Universität des Saarlandes, Saarbrücken</td>
<td>GaN MEMS and NEMS</td>
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<td>Matthias Schreck</td>
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<td>Thomas Seylter</td>
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<td>Robert Tampé</td>
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<td>Marc Tornow</td>
<td>Universität Braunschweig</td>
<td>Biosensors, molecular electronics</td>
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<td>Klaus Wandelt</td>
<td>Universität Bonn</td>
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<td>Werner Wegscheider</td>
<td>Universität Regensburg</td>
<td>Molecular beam epitaxy, cleaved edge overgrowth quantum wires and dots</td>
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<td>Hartmut Wiggers</td>
<td>Universität Duisburg-Essen</td>
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<td>Achim Wixforth</td>
<td>Universität Augsburg</td>
<td>SAW control of quantum dot and quantum wire nanostructures</td>
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<td>Jörg Wrachtrup</td>
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<tr>
<td>Artur Zrenner</td>
<td>Universität Paderborn</td>
<td>Single quantum dot photodiodes</td>
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- Tobias Pirzer
- Ulrich Rant
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- Andrea Mückl
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- Hubert Riedl
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- Anna Cattani-Scholz
- Frank Fischer
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- Eric Hoffmann
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- Hua Li (Humboldt Research Fellow)
- Hideyuki Maki, Keio University, Japan
- Vladimir Mitin (Humboldt Senior Fellow)
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Shuit Tong Lee, FUNSOM, Suzhou, China

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Shamsul Araf
Per-Lennart Ardelt
Vera Arnaut
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Moritz Hauf
Norman Hauke
Simon Hertenberger
Lucas Hess
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Günther Reithmaier
Katharina von Roman
Daniel Rudolph
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Kai Saller
Susanne Schäfer
Max Boy Scheible
Matthias Schickinger
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Sebastian Schöll
Konrad Schraml
Robert Schrobenhauser
Fabian Schuster
Markus Schuster
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Narayan Sircar
Jean-Philippe Sobczak
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Stephan Sprengel
Evi Stahl
Markus Stallhofer
Benedikt Stoib
Maximilian Suckert
Mario Teichmann
Julian Treu
Ganpath Kumar Veerabathran
Valentina Villa
Augustinas Vizbaras
Kristijonas Vizbaras
Christian Wachauf
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Thomas Welte
Andreas Wild
Jakob Wierzbowski
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Simon Pfaehler
Timo Preißing
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Felix Rolf
Tilman Schimpke
Tobias Schneider
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Karl Philipp Kunze*

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Vitaly Loggvynenko*
Günther Pardatscher
Julius Rombach*
Manuel Salzberger*
Hannah Schamoni*
Enrique Lin Shiao
Anna Vernichel*
Daniela Ziegler*
5. Doctoral, Diploma, Bachelor and Master Theses

Doctoral Theses

1. *Modeling of Leakage Currents in High-κ Dielectrics*
   Christian Jegert (01/2012)

2. *Electrically-Pumped GaSb-Based Vertical-Cavity Surface-Emitting Lasers*
   Shamsul Arafim (01/2012)

3. *Enhanced spontaneous emission from silicon-based photonic crystal nanostructures*
   Norman Hauke (02/2012)

4. *Quantum spin transport in semiconductor nanostructures*
   Christoph Schindler (05/2012)

5. *Group IV all-semiconductor spintronics: Materials aspects and optical spin selection rules*
   Narayan Sircar (05/2012)

6. *Correlated behavior of electrostatically trapped dipolar excitons at low temperatures*
   Georg Schinner (05/2012)

7. *Electron Spin Resonance Investigation of Semiconductor Materials for Application in Thin-Film Silicon Solar Cells*
   Lihong Xiao (06/2012)

8. *Molecular cascades based on DNA origami platforms*
   Mario Teichmann (6/2012)

9. *Hybrid organic-inorganic heterojunctions for photovoltaic applications*
   Roland Dietmüller (07/2012)

10. *Growth and Properties on In(Ga)As Nanowires on Silicon*
    Simon Hertenberger (08/2012)

11. *Study on silicon-germanium nanoislands as emitters for a monolithic silicon light source*
    Thomas Zabel (09/2012)

12. *Theory of the Electronic Structure of Quantum Dots in External Fields*
    Thomas Eißfeller (09/2012)

13. *Spin effects in self-assembled semiconductor quantum dots*
    Florian Klotz (10/2012)
14. **Antimonide-based vertical-cavity surface-emitting lasers**  
   Vase Jovanov (10/2012)

15. **Electrical Detection of Hyperfine Interactions in Silicon**  
   Felix Hoehne (11/2012)

16. **Comparison of Different Ionisation Techniques for Ion Mobility**  
   Carola Oberhüttinger (11/2012)

17. **DNA Origami based plasmonic arrays**  
   Jonathan List (11/2012)

18. **Electroosmotic Flow and Protein Trappig in Solid-State Nanopores**  
   Matthias Firnkes (12/2012)

19. **Efficient calculation of dissipative quantum transport in semiconductor nanostructures**  
   Peter Greck (12/2012)

20. **Novel thin film concepts for photovoltaic applications**  
    Tobias Antesberger (12/2012)

21. **GaN Heterostructures for Biosensing and Radiation Detection**  
    John Howgate (12/2012)

22. **Hybrid polymer/silicon nanocrystal solar cells**  
    Sabrina Niesar (12/2012)

23. **Electronic properties of electrolyte-gated diamond FETs for bioelectronics applications**  
    Markus Dankerl (12/2012)

24. **Interfaces in nitride devices**  
    Olaf Weidemann (12/2012)

25. **Epitaxial growth and characterization of Zn(Mg)O thin films**  
    Thomas Wassner (12/2012)

**Diploma Theses**

1. **Photonic Nanostructures for Physical Crytography**  
   Raphael Knobling (01/2012)

2. **Bio-molecular hybrid systems for energy harvesting**  
   Michael Metzger (05/2012)

3. **Ultra low leakage current silicon p-i-n diodes for resonant photocurrent spectroscopy on Germanium islands**  
   Thorsten Reichert (05/2012)
4. *Prozesstechnologische Optimierung Antimon-basierter Metall-Halbleiter Kontakte*  
   Kathrin Geiger (05/2012)

5. *Theoretical investigation of integrated plasmonic structures in SOI-Technology*  
   Nesrine Kammoun (06/2012)

6. *Switchable molecular structures on DNA origami platforms*  
   Enzo Kopperger (06/2012)

7. *Tailoring of Quantum dot nanostructures*  
   Johannes Wildmann (06/2012)

8. *Plasmon-mediated excitation of single quantum dots*  
   Mäx Blauth (06/2012)

9. *Hochauflösende Zweipunkt-Abstandsmessungen für die Proteinanalyse*  
   Jonas Funke (07/2012)

10. *DNA-Origami funktionalisierte Festkörpernanoporen*  
    Leonhard Sturm (07/2012)

11. *Optical and magneto-optical spectroscopy in coupled quantum dots*  
    Andreas Waebber (07/2012)

12. *Thermoelektrische Grundlagen dünner Si-Ge-Schichten*  
    Tim Langmann (08/2012)

13. *Graphene based solution-gated field-effect transistors*  
    Benno Blaschke (08/2012)

14. *Elektronische Eigenschaften nanostrukturierter Siliziumoberflächen*  
    Julie Paye (09/2012)

15. *Construction of a Micro-Photoluminescence Setup and Measurements on InAs/InGaAs Nanowires*  
    Liang Mengyu (09/2012)

16. *Photoconductance of gold nanoparticle arrays*  
    Johannes Schopka (09/2012)

17. *Tailoring Light Matter Interactions in Nanoparticle Plasmonic Hybrid Systems*  
    Benedikt Mayer (10/2012)

18. *Elektronische Eigenschaften von Nanopartikeln aus Verbindungshalbleitern*  
    Willi Aigner (10/2012)

19. *Hochauflösende Einzelmolekül-Kraftspektroskopie an DNA-Molekülen*  
    Emanuel Pfitzner (10/2012)
20. Development of superconducting single-photon detectors for on-chip quantum optics
   Jörg Senf (10/2012)

21. Towards Gate Induced Two-Dimensional Electron Gases in 28Si/SiGe Heterostructures
   Christoph Buhlheller (10/2012)

22. Studien zur Realisierung einer nanoskopischen organischen Leuchtdiode auf der Spitze einer Rasterkraftsonde”
   Benjamin Martini (10/2012)

23. Akustische EPR mit Oberflächenwellen
   Alexander Kupijai (11/2012)

24. Transport in graphene nanostructures
   Eric Parzinger (11/2012)

25. MBE growth of GaN-based materials for high temperature thermoelectrics
   Bernhard Loitsch (11/2012)

26. Epitaxie und Charakterisierung von III-Nitrid-Nanodrähten
   Andrea Winnerl (11/2012)

27. Breitbandige EDMR-Messungen an Bismuth-dotiertem Silizium
   Florian Hrubesch (11/2012)

28. Mid-Infrared Light Generation on InP. Extending the Wavelength Limit of III/V Alloy Heterostructures on InP Substrate – Simulation, Growth via MOVPE and Characterization
   Peter Wiecha (11/2012)

29. Konzeptionierung, Design und Realisierung Monolithisch Integrierter MEMS Vertikalresonator Laserdioden - Der MIMS VCSEL -
   Christian Herzing (11/2012)

30. Probing ultrafast charge and spin dynamics in a single self-assembled quantum dot
   Timo Kaldewey (11/2012)

31. In situ laser lithography for realizing tunable photonic nanostructures
   Alexander Büse (11/2012)

32. Simulation and optical characterization of plasmonic bowtie nanoantennas
   Mathias Kammerlocher (11/2012)

33. Structural analysis of InGaAs nanowires via μ-photoluminescence spectroscopy
   Lucas Schweickert (11/2012)

34. Laser cooling of bosonic and fermionic lithium
   Timon Hilker (11/2012)
35. Development and characterization of on-chip plasmonic devices
Jakob Wierzbowski (11/2012)

Johannes Röthinger (11/2012)

37. Dynamics of Electrically Switchable DNA Layers on Gold Electrodes
Philip Schwertler (11/2012)

38. Polarization controlled photocurrents in topological insulators
Christoph Karnetzky (11/2012)

39. InP-based 1.55 µm-short cavity VCSELs for high-speed optical fiber telecommunication with stacked active region
Alexander Andrejew (12/2012)

40. Functionalization of electrolyte-gated organic field-effect transistors
Andreas Donner (12/2012)

41. Nanoscale diamond field effect transistors
Patrick Simon (12/2012)

42. Fabrication and characterization of vertical surroundgate and planar top- and backgate InAs Nanowire Field Effect Transistors
Verena Hintermayr (12/2012)

43. Polarized Raman Spectroscopy on Organophosphonate-Based Thin Films
Dominik Weinbrenner (12/2012)

44. Superposition und Visualisierung von akustischen Oberflächen
Richard Rambach (12/2012)

**Master Theses**

1. Experimental setup of micro-photoluminescence spectroscopy for InAs-based and infrared nanostructured materials
Kun Chen (05/2012)

2. Entwicklung kurzwelliger Quanten-Kaskaden-Laser bei 3,3 µm durch Generation der zweiten Harmonischen
Dina Alfimova (08/2012)

3. Optical investigations of spin phenomena in resonantly excited quantum dot nanostructures
Sebastian Koch (10/2012)

4. Oszillators / Coordination of molecular processes with a synthetic biochemical oscillator
Matthaeus Schwarz-Schilling(10/2012)
5. *Charge Transport in InAs Nanowires*
   Philipp Geselbracht (10/2012)

6. *Einzelmoleküluntersuchungen auf lithographisch angeordneten DNA-Origamistrukturen*
   Günther Pardatscher (10/2012)

7. *Optical investigations of spin phenomena in resonantly excited quantum dot nanostructures*
   Sebastian Koch (10/2012)

8. *Spatially resolved electronic properties of III-V NW Systems*
   Tao Yang (11/2012)

9. *Superposition un Visualisierung von akustischen Oberflächen*
   Richard Rambach (12/2012)

**Bachelor Theses**

1. *Elektrische Charakterisierung zufälliger pn-Dioden für die Kryptographie*
   Julius Rombach (03/2012)

2. *Influence of film morphology on the sensitivity of electrolyte-gated organic field-effect transistors*
   Hannah Schamoni (07/2012)

3. *Hybrid solar cells with silicon nanocrystals*
   Jochen Bissinger (07/2012)

4. *Charakterisierung von ZnO-Schichten auf Diamantsubstrat*
   Martin Hetzl (07/2012)

5. *Ultraschnelle Photoströme und THz-Erzeugung in einzelnen InAs Nanodrähten*
   Paul Seifert (07/2012)

6. *Electrical characterization of functionalized diamond surfaces for bio-applications*
   Anna Vernickel (08/2012)

7. *Investigation of charge noise in 2D electron systems in Si/SiGe heterostructures*
   Manuel Salzberger (08/2012)

8. *Elektronenspinresonanz paramagnetischer Defekte in Silizium*
   Markus Krottenmüller (08/2012)

9. *Optoelectronic Properties of Gold Nanorods*
   Sebnem Tuncay (08/2012)
10. *Fluorescence enhancement of implanted CdSe nanocrystals by proximal plasmomic nanoparticle arrays*  
Lisa Kugler (09/2012)

11. *Development of GaAs optical waveguides for integration with superconducting nanowires detectors*  
Raphael Jakoby (09/2012)

12. *Optical properties of InGaAs/GaAs nanowire heterostructures*  
Anh Tu Bohn (09/2012)

Fabian Flassig (10/2012)

14. *Photonic crystals - control of light at the nanoscale*  
Miriam Müting (10/2012)

15. *Tailoring Self-Assembled Quantum Dot Molecule Diode Structure*  
Julian Klein (10/2012)

16. *Coherence Measurements of Plasmonic Structures*  
Julia Wembacher (10/2012)
6. Publications

• **ZnO/(ZnMg)O single quantum wells with high Mg content graded barriers**
  B. Laumer, F. Schuster, T. Wassner, M. Stutzmann, M. Rohnke, J. Schörmann, and M. Eickhoff

• **Ultrahigh gain AlGaN/GaN high energy radiation detectors**

• **Laser-sintered thin films of doped SiGe nanoparticles**
  B. Stoib, T. Langmann, S. Matich, T. Antesberger, N. Stein, S. Angst, N. Petermann, R. Schmechel, G. Schierning, D. E. Wolf, H. Wiggers, M. Stutzmann, and M. S. Brandt

• **In vitro bio-functionality of gallium nitride sensors for radiation biophysics**

• **Growth study of nonpolar Zn1-xMgxO epitaxial films on a-plane bulk ZnO by plasma-assisted molecular beam epitaxy**

• **Low-cost post-growth treatments of crystalline silicon nanoparticles improving surface and electronic properties**
  S. Niesar, R. N. Pereira, A. R. Stegner, N. Erhard, M. Hoeb, A. Baumer, H. Wiggers, M. S. Brandt, and M. Stutzmann

• **Lock-in detection for pulsed electrically detected magnetic resonance**
  F. Hoehne, L. Dreher, J. Behrends; M. Fehr, H. Huebl, K. Lips, A. Schnegg, M. Suckert, M. Stutzmann, and M. Brandt

• **Self-Assembled GaN Nanowires on Diamond**
• Platinum Nanoparticles on Gallium Nitride Surfaces: Effect of Semiconductor Doping on Nanoparticle Reactivity
  S. Schäfer, S. A. Wyrzgol, R. Caterino, A. Jentys, S. J. Schoell, M. Hävecker, A.
  Knop-Gericke, J. A. Lercher, I. D. Sharp and M. Stutzmann

• Thermodynamic Efficiency Limit of Molecular Donor-Acceptor Solar Cells and its Application to Diindenoperylene/C60-Based Planar Heterojunction Devices

• Solid polyelectrolyte-gated surface conductive diamond field effect transistors
  M. Dankerl, M. Tosun, M. Stutzmann, and J. A. Garrido

• Nuclear Spins of Ionized Phosphorus Donors in Silicon
  L. Dreher, F. Hoehne; M. Stutzmann, and M. S. Brandt

• Charge state manipulation of qubits in diamond
  B. Grotz, M. Hauf, M. Dankerl, B. Naydenov, S. Pezzagna, J. Meijer, F. Jelezko, J.
  Wrachtrup, M. Stutzmann, F. Reinhard, and J. A. Garrido

• Biofunctional Electrolyte-Gated Organic Field-Effect Transistors
  F. Buth, A. Donner, M. Sachsenhauser, M. Stutzmann, and J. A. Garrido
  Adv. Mat. 24, 4511 (2012)

• Diamond solution-gated field effect transistors: Properties and bioelectronics applications
  M. Dankerl, M. Hauf, M. Stutzmann, and J. A. Garrido
  phys. stat. sol. (a) 209 (2012)

• Direct in situ transmission electron microscopy observation of Al push up during early stages of the Al-induced layer exchange
  B. I. Birajadar, T. Antesberger, B. Butz, M. Stutzmann, and E. Spiecker

• Fabrication of large-grained thin polycrystalline silicon films on foreign substrates by titanium-assisted metal-induced layer exchange
  T. Antesberger, T. Wassner, M. Kashani, M. Scholz, R. Lechner, S. Matich, and M.
  Stutzmann

• Rapid folding of DNA into nanoscale shapes at constant temperature
  J. Sobczak, T. Martin, T. Gerling, H. Dietz
The cryo-EM structure of a 3D DNA-origami object
X. Bai, T. Martin, S. Scheres, and H. Dietz
PNatl Acad Sci USA, vol. 109, 20012 (2012), (cover story)

Synthetic lipid membrane channels formed by designed DNA nanostructures

Magnesium-free self-assembly of multi-layer DNA objects
T. Martin and H. Dietz

DNA origami gatekeepers for solid-state nanopores
R. Wei*, T. Martin*, U. Rant, and H. Dietz

Quantitative prediction of 3D solution shape and flexibility of nucleic acid nanostructures
D. Kim, F. Kilchherr, H. Dietz, and M. Bathe

Distance dependence of single-fluorophore quenching by gold nanoparticles studied on DNA origami
ACS Nano 6, 3189-3195 (2012)

Probing DNA-lipid membrane interactions with a lipopeptide nanopore
A. Bessonov, J. Takemoto, F. C. Simmel
ACS Nano 6, 3356-3363 (2012)

DNA-based self-assembly of chiral plasmonic nanostructures with tailored optical response

Synthetic in vitro transcription circuits
M. Weitz, and F. C. Simmel
Transcription 3, 87-91 (2012)

DNA-based assembly lines and nanofactories
F. C. Simmel
Current Opinion in Biotechnology 23, 516-521 (2012)
• **Quantitative Analysis of the Nanopore Translocation Dynamics of Simple Structured Polynucleotides**

• **Nanoscale imaging in DNA nanotechnology**
  R. Jungmann, M. Scheible, and F. C. Simmel
  WIREs Nanomedicine & Nanobiotechnology **4**, 66-81 (2012)

• **Photocurrent of a single photosynthetic protein**
  D. Gerster, J. Reichert, H. Bi, J. V. Barth, S. M. Kaniber, A.W. Holleitner, I. Visoly-Fisher, S. Sergani, I. Carmeli

• **Time-resolved ultrafast photocurrents and terahertz generation in freely suspended graphene**
  L. Prechtel, L. Song, D. Schuh, P. Ajayan, W. Wegscheider, A.W. Holleitner
  Nature Communications **3**, 646 (2012)

• **Local photocurrent generation in thin films of the topological insulator Bi2Se3**
  C. Kastl, T. Guan, X. Y. He, K. H. Wu, Y. Q. Li, A. W. Holleitner

• **Time-resolved photoinduced thermoelectric and transport currents in GaAs nanowires**
  L. Prechtel, M. Padilla, N. Erhard, H. Karl, G. Abstreiter, A. Fontcuberta i Morral, A.W. Holleitner
  Nano Letters **12**, 2337 (2012)

• **Tunable photo-emission from an excitonic antitrap**
  K. Kowalik-Seidl, X. Vögele, B. Rimpfl, G. Schinner, D. Schuh, W. Wegscheider, A. W. Holleitner, and J.P. Kotthaus

• **Electrical control of inter-dot electron tunneling in a double InGaAs quantum-dot nanostructure**

• **Negative Differential Photoconductance in Gold Nanoparticle Arrays in the Coulomb Blockade Regime**
  M. Mangold, M. Calame, M. Mayor, A.W. Holleitner
  ACS Nano **6**, 4181 (2012)
- Propagation length of mesoscopic photocurrents in a two-dimensional electron gas
Markus Stallhofer, Christoph Kastl, Marcel Brändlein, Christoph Karnetzky, Dieter Schuh, Werner Wegscheider, and Alexander W. Holleitner,

- Enlarged magnetic focusing radius of photoinduced ballistic currents
Markus Stallhofer, Christoph Kastl, Marcel Brändlein, Dieter Schuh, Werner Wegscheider, Jörg P. Kotthaus, Gerhard Abstreiter, and Alexander W. Holleitner
Physical Review B 86, 115315 (2012)

- Sub-diffraction optical coherent control of ultrafast electrical currents in antenna devices on GaAs
S. Thunich, C. Ruppert, A. W. Holleitner, M. Betz

- Broadband Purcell enhanced emission dynamics of quantum dots in linear photonic crystal waveguides
Laucht, T. Günthner, S. Pütz, R. Saive, S. Frederick, N. Hauke, M. Bichler, M. C. Amann, A.W. Holleitner, M. Kaniber, and J. Finley

- A waveguide-coupled on-chip single photon source
Laucht, S. Pütz, T. Günthner, N. Hauke, R. Saive, S. Frédérick, M. Bichler, M.-C. Amann, A. W. Holleitner, M. Kaniber, J. J. Finley
Physical Review X 2, 011014 (2012)

- Surface functionalization of 6H-SiC using organophosphonate monolayers

- Coupling of guided surface plasmon polaritons to proximal self-assembled InGaAs quantum dots
G. Bracher, K. Schraml, M. Blauth, C. Jakubeit, G. Koblmüller, K. Mueller, M. Bichler, M. Kaniber, and J. J. Finley

- Molecular Architecture: Construction of Self-Assembled Organophosphonate Duplexes and Their Electrochemical Characterization

- Photocurrent of a single photosynthetic protein
D. Gerster, J. Reichert, H. Bi, J. V. Barth, S. M. Kaniber, A.W. Holleitner, I. Visoly-Fisher, S. Sergani, I. Carmeli
Nature Nanotechnology 7, 673 (2012)
• Solution processable carbon nanotube network thin-film transistors operated in electrolytic solutions at various pH
  T. Haeberle, A. Münzer, F. Buth, J. A. Garrido, A. Abdellah, B. Fabel, P. Lugli, and G. Scarpa

• A three-dimensional silicon photonic crystal nanocavity with enhanced emission from embedded germanium islands

• High composition homogeneity in In-rich InGaAs nanowire arrays on nanoimprinted SiO2/Si (111)

• Rate-limiting mechanisms in high-temperature growth of catalyst-free InAs nanowires with large thermal stability
  S. Hertenberger, D. Rudolph, J. Becker, M. Bichler, J. J. Finley, G. Abstreiter, and G. Koblmüller
  Nanotechnology 23, 235602 (2012)

• Optimization of AlAs/AlGaAs quantum well heterostructures on on-axis and misoriented GaAs (111) B
  F. Herzog, M. Bichler, G. Koblmüller, S. Prabhu-Gaunkar, W. Zhou, and M. Grayson

• All optical preparation, storage, and readout of a single spin in an individual quantum dot
  V. Jovanov, F. Klotz, S. Kapfinger, D. Heiss, S. Spiga, D. Rudolph, M. Bichler, M. S. Brandt, G. Abstreiter, and J. J. Finley
  Proc. SPIE 8272, 827211 (2012)

• Highly nonlinear excitonic Zeeman spin splitting in composition-engineered artificial atoms
  V. Jovanov, T. Eissfeller, S. Kapfinger, E. Clark, F. Klotz, M. Bichler, J. G. Keizer, P. M. Koenraad, M. S. Brandt, G. Abstreiter, and J. J. Finley

• Local photocurrent generation in thin films of the topological insulator Bi2Se3
  C. Kastl, T. Guan, X. Y. He, K. H. Wu, Y. Q. Li, A. W. Holleitner
• *Quantitation of affinity, avidity, and binding kinetics of protein analytes with a dynamically switchable biosurface*
  Jelena Knezevic, Andreas Langer, Paul A. Hampel, Wolfgang Kaiser, Ralf Strasser, and Ulrich Rant

• *Diameter dependent optical emission properties of InAs nanowires grown on Si*

• *Tunable photo-emission from an excitonic antitrap*
  K. Kowalik-Seidl, X. Vögele, B. Rimpf, G. Schinner, D. Schuh, W. Wegscheider, A. W. Holleitner, and J.P. Kotthaus
  Nano Letters 12, 326 (2012)

• *Broadband Purcell enhanced emission dynamics of quantum dots in linear photonic crystal waveguides*
  A. Laucht, T. Günthner, S. Pütz, R. Saive, S. Frederick, N. Hauke, M. Bichler, M. C. Amann, A. Holleitner, M. Kaniber, and J. J. Finley

• *A Waveguide-Coupled On-Chip Single-Photon Source*
  A. Laucht, S. Pütz, T. Günthner, N. Hauke, R. Saive, S. Frederick, M. Bichler, M. C. Amann, A. Holleitner, M. Kaniber, and J. J. Finley

• *Fluctuation induced luminescence sidebands in the emission spectra of resonantly driven quantum dots*

• *Climbing the Jaynes-Cummings ladder by photon counting*
  F. P. Laussy, E. del Vallo, M. Schrapp and J. J. Finley
  Journal of Nanophotonics, 6, 061803, (2012)

• *Universal signatures of lasing in the strong coupling regime*
  F. P. Laussy, Elena del Vallo, M. Schrapp and J. J. Finley

• *Heat flow in InAs/InP heterostructure nanowires*
  J. Matthews, E. Hoffmann, C. Weber, A. Wacker, and H. Linke
• **Negative Differential Photoconductance in Gold Nanoparticle Arrays in the Coulomb Blockade Regime**  
  M. Mangold, M. Calame, M. Mayor, and A. Holleitner  
  ACS Nano 6, 4181 (2012)

• **Optoelectronic properties of OLEC devices based on phenylquinoline and phenylpyridine ionic iridium complexes**  
  E. Margapoti, M. Muccini, A. Sharma, A. Colombo, C. Dragonetti, A. Valore, and D. Roberto  
  Dalton Transaction, 41, 9227-9231 (2012)

• **Paramagnetic shift in thermally annealed CdxZn1-xSe quantum dots**  

• **1.3um High-Power Short-Cavity VCSELs for High-Speed Applications**  
  M. Müller, C. Grasse, K. Sailer, T. Gruendl, G. Boehm, M. Ortsiefer, and M. C. Amann  
  Proceedings of Conference on Lasers and Electro-Optics (CLEO) and Quantum Electronics Laser Science Conference (QELS), May 6 - 11 in San José, CA, USA (2012)

• **All optical quantum control of a spin-quantum state and ultrafast transduction into an electric current**  

• **Electrical Control of Interdot Electron Tunneling in a Double InGaAs Quantum-Dot Nanostructure**  

• **High fidelity optical preparation and coherent Larmor precession of a single hole in an InGaAs quantum dot molecule**  

• **Probing ultrafast charge and spin dynamics in a quantum dot molecule**  
• *Time-resolved photoinduced thermoelectric and transport currents in GaAs nanowires*
  L. Prechtel, M. Padilla, N. Erhard, H. Karl, G. Abstreiter, A. Fontcuberta i Morral, and A. Holleitner

• *Time-resolved ultrafast photocurrents and terahertz generation in freely suspended graphene*
  L. Prechtel, L. Song, D. Schuh, P. Ajayan, W. Wegscheider, and A. Holleitner
  Nature Communications 3, 646 (2012)

• *Sensing with electro-switchable biosurfaces*
  U. Rant
  Bioanal. Rev. 4, 97 (2012)

• *Covalent attachment of functionalized cardiolipin on a biosensor gold surface allows repetitive measurements of anti-cardiolipin antibodies in serum*

• *Quantum dynamics of damped and driven anharmonic oscillators*
  M. Schrapp, E. del valle, J. J. Finley and F. P. Laussy

• *Surface acoustic wave controlled charge dynamics in a thin InGaAs quantum well*
  F. Schülein, J. Pustiowski, K. Mueller, M. Bichler, G. Koblmüller, J. J. Finley, A. Wixforth, and H. Krenner
  JETP Letters 95, 11, 653 (2012)

• *Valence band structure of polytypic zinc-blende/wurtzite GaAs nanowires probed by polarization-dependent photoluminescence*
  Physical Review B 85, 045309 (2012)

• *Enlarged magnetic focusing radius of photoinduced ballistic currents*
  M. Stallhofer, C. Kastl, M. Brändlein, D. Schuh, W. Wegscheider, J. Kotthaus, G. Abstreiter, and A. Holleitner

• *Propagation length of mesoscopic photocurrents in a two-dimensional electron gas*
  M. Stallhofer, C. Kastl, M. Brändlein, C. Karnetzky, D. Schuh, W. Wegscheider, and A. Holleitner
• *Messung molekularer Interaktion mit dynamischen Oberflächensensoren*
  R. Strasser, D. Scholl, P. Hampel, A. Langer, and U. Rant
  BIOspektrum **18** (7), 724 (2012)

• *Sub-diffraction optical coherent control of ultrafast electrical currents in antenna devices on GaAs*
  S. Thunich, C. Ruppert, A. W. Holleitner, and M. Betz

• *Substrate orientation dependent fine structure splitting of symmetric In(Ga)As/GaAs quantum dots*
  J. Treu, C. Schneider, A. Huggenberger, T. Braun, S. Reitzenstein, S. Höfling, and M. Kamp

• *DNA origami gatekeepers for solid-state nanopores*
  R. Wei, T. G. Martin, U. Rant, and Hendrik Dietz

• *Stochastic Sensing of Proteins with Receptor-Modified Solid-State Nanopores*
  Ruoshan Wei, Volker Gatterdam, Ralph Wienke, Robert Tampé, and Ulrich Rant

• *Few electron double quantum dot in an isotopically purified 28Si quantum well*

• *Size, composition and doping effects on In(Ga)As nanowire/Si tunnel diodes probed by conductive atomic force microscopy*
  T. Yang, S. Hertenberger, S. Morkötter, G. Abstreiter, and G. Koblmüller

• *Pressure Tuning of the Optical Properties of GaAs Nanowires*
  I. Zardo, S. Yazji, C. Marini, E. Uccelli, A. Fontcuberta i Morral, G. Abstreiter, and P. Postorino
  ACS Nano **6** (4), 3284-3291 (2012)

• *Photoinduced growth of DNA capped silver nanoparticles*
  V. B. Zon, G. Burley, and U. Rant
  Nanotechnology **23**, 115607 (2012)

• *Discrete Tomography of Demanding Samples Based on a Modified SIRT Algorithm*
  A. Zürner, M. Döblinger, V. Cauda, R. Wei, and T. Bein
  Ultramicroscopy **115**, 41-49 (2012)
- **1.3 µm short-cavity VCSELs enabling error-free transmission at gbit/s over 25 km fibre link**
  M. Mueller, P. Wolf, C. Grasse, M. P. I. Dias, M. Ortsiefer, G. Boehm, E. Wong, W. Hofmann, D. Bimberg, and M.-C. Amann

- **1.3 µm high-power short-cavity VCSELs for high-speed applications**
  M. Mueller, C. Grasse, K. Saller, T. Gruendl, G. Boehm, M. Ortsiefer, and M.-C. Amann
  Proc. of Conference on Lasers and Electro-Optics (CLEO) and Quantum Electronics Laser Science Conference (QELS), San Jose, USA (2012)

- **100 Gb/s single VCSEL data transmission link**
  OFC/NFOEC, Los Angeles, USA (2012)

- **30-Gbit/s OFDM intensity modulation of 1550-nm VCSEL**
  Asia Communications and Photonics Conference, Guangzhou, China, Page AS3C.1 (2012)

- **50 nm continuously tunable MEMS VCSEL devices with surface micromachining operating at 1.95 µm emission wavelength**

- **A waveguide-coupled on-chip single-photon source**
  A. Laucht, S. Puetz, T. Guenther, N. Hauke, R. Salve, S. Frederick, M. Bichler, M.-C. Amann, A. Holleitner, M. Kaniber, and J. Finley

- **AlGaInAsPSb-based high-speed short-cavity VCSEL with single-mode emission at 1.3 µm grown by MOVPE on InP substrate**
  16th International Conference on Metal Organic Vapor Phase Epitaxy, Busan, South Korea (2012)

- **All optical preparation, storage, and readout of a single spin in an individual quantum dot**
  V. Jovanov, F. Klotz, S. Kapfinger, D. Heiss, S. Spiga, D. Rudolph, M. Bichler, M. S. Brandt, G. Abstreiter, and J. Finley
  Proc. of SPIE 8272, 827211 (2012)
• *Arithmetical elimination of superimposed interference modulation in laser spectroscopic gas concentration measurements*
  A. Hartmann, R. Strzoda, R. Schrobenhauser, and R. Weigel

• *Broadband purcell enhanced emission dynamics of quantum dots in linear photonic crystal waveguides*
  A. Laucht, T. Guenthner, S. Puetz, R. Salve, S. Frederick, N. Hauke, M. Bichler, M.-C. Amann, A. Holleitner, M. Kaniber, and J. Finley

• *Detection of the mass of airborne particles in an online optical sensor system by correlation of geometric and inertial filtering*
  R. Schrobenhauser, R. Strzoda, M. Fleischer, and M.-C. Amann

• *Diameter dependent optical emission properties of InAs nanowires grown on Si*

• *Energy saving strategies for VCSEL ONU*
  E. Wong, M. Mueller, M. P. I. Dias, C. A. Chan, and M.-C. Amann
  OFC/NFOEC, Los Angeles, USA (2012)

• *Energy-efficiency of optical network units with vertical-cavity surface-emitting lasers*
  E. Wong, M. Mueller, M. P. I. Dias, C. A. Chan, and M.-C. Amann

• *Energy-efficient 1.3 µm short-cavity VCSELs for 30 Gb/s error-free optical links*
  23rd IEEE International Semiconductor Laser Conference (ISLC), San Diego, USA (2012)

• *Energy-efficient high-speed short-cavity VCSELs*
  M.-C. Amann, E. Wong, and M. Mueller
  OFC/NFOEC, Los Angeles, USA, paper OTh4F (2012)

• *Extending lasing wavelength on InP with GaAsSb/GaInAs type-II active regions*
  S. Sprengel, K. Vizbaras, A. Andrejew, T. Gruendl, K. Geiger, G. Boehm, C. Grasse, and M.-C. Amann
  23rd IEEE International Semiconductor Laser Conference (ISLC), San Diego, USA (2012)
• *GaInAs/GaAsSb-based type-II micro-cavity LED with 2-3 μm light emission grown on InP substrate*
  C. Grasse, T. Gruendl, S. Sprengel, P. Wiecha, K. Vizbaras, R. Meyer, and M.-C. Amann
  16th International Conference on Metal Organic Vapor Phase Epitaxy, Busan, South Korea (2012)

• *GaSb- and InP-based devices for mid-infrared gas sensing application*
  C. Grasse, K. Vizbaras, S. Sprengel, and M.-C. Amann
  International Workshop on Opportunities and Challenges in Mid-Infrared Laser-Based Gas Sensing, Wroclaw, Poland (2012)

• *High composition homogeneity in In-rich InGaAs nanowire arrays on nanoimprinted SiO2/Si (111)*

• *Highly sensitive laser-based sensor for nanoparticles in air using a dual-ring-mirror setup*
  R. Schrobenhauser, R. Strzoda, M. Fleischer, and M.-C. Amann

• *InP based type-II resonant cavity LEDs emitting up to 3.5 μm*
  P. Wiecha, C. Grasse, S. Sprengel, T. Gruendl, R. Meyer, and M.-C. Amann
  27. DGKK Workshop, Erlangen, Germany (2012)

• *InP-based 1.3 μm and 1.55 μm short-cavity VCSELs suitable for Telecom- and Datacom-applications*
  M. Mueller, C. Grasse, and M.-C. Amann
  International Conference on Transparent Optical Networks (ICTON), Warwick, United Kingdom, paper MO.B4.2 (2012)

• *InP-based 2.8-3.5 μm resonant-cavity light emitting diodes based on type-II transitions in GaInAs/GaAsSb heterostructures*
  C. Grasse, P. Wiecha, T. Gruendl, S. Sprengel, R. Meyer, and M.-C. Amann

• *Long-wavelength VCSELs for sensing applications*
• Nanoparticle detection in a miniaturized setup using laser beam shaping and dual angle information provided by fresnel ring lenses
  R. Schrobenhauser, R. Strzoda, M. Fleischer, and M.-C. Amann

• New standards in high-speed and tunable long wavelength VCSELs
  T. Gruendl, M. Mueller, and M.-C. Amann

• Nonlinear GaInAs/AlInAs/InP quantum cascade laser sources for wavelength generation in the 2.7-70 µm wavelength range
  A. Vizbaras, R. W. Adams, C. Grasse, M. Jang, R. Meyer, M. A. Belkin, and M.-C. Amann
  SPIE Photonics West Vol. 8268, San Francisco, USA (2012)

• Recent results on long-wavelength VCSELs: Device structures, performance and applications
  T. Gruendl, M. Mueller, C. Grasse, K. Vizbaras, and M.-C. Amann
  IEEE Photonics Conference (IPC), San Francisco, USA (2012)

• Room-temperature 3.73 µm GaSb-based type-I quantum-well lasers with quinternary barriers
  K. Vizbaras, and M.-C. Amann
  Semiconductor Science and Technology Vol. 27 (3), 032001 (2012)

• Room-temperature type-I GaSb-based lasers in the 3.0-3.7 µm wavelength range
  K. Vizbaras, A. Vizbaras, A. Andrejew, C. Grasse, S. Sprengel, and M.-C. Amann
  SPIE Photonics West, San Francisco, USA (2012)

• Short-wavelength InP quantum cascade laser sources by quasi-phase-matched intracavity second-harmonic generation
  Physica Status Solidi (c) Vol. 9, No. 2, pp. 298-301 (2012)

• Terahertz quantum cascade laser sources based on Cherenkov intra-cavity difference-frequency generation
  K. Vijayraghavan, R. W. Adams, A. Vizbaras, M. Jang, C. Grasse, G. Boehm, M.-C. Amann, and M. A. Belkin
  Proc. of CLEO, San Jose, USA (2012)

• Terahertz sources based on Cherenkov difference-frequency generation in quantum cascade lasers
  K. Vijayraghavan, R. W. Adams, A. Vizbaras, M. Jang, C. Grasse, G. Boehm, M.-C. Amann, and M. A. Belkin
• **Type-II InP-based lasers emitting at 2.55 µm**
  S. Sprengel, A. Andrejew, K. Vizbaras, T. Gruendl, K. Geiger, G. Boehm, C. Grasse, and M.-C. Amann

• **Type-II quantum wells for InP based mid-IR devices**
  T. Gruendl, C. Grasse, P. Wiecha, S. Sprengel, and M.-C. Amann
  Mid-Infrared Optoelectronics: Materials and Devices MIOMD, Chicago, USA (2012)

• **Type-II quantum wells on InP emitting up to 3.2 µm**
  S. Sprengel, K. Vizbaras, C. Grasse, A. Andrejew, T. Gruendl, K. Geiger, G. Boehm, and M.-C. Amann
  International Nano-Optoelectronics Workshop (iNOW), Berkeley & Stanford, USA (2012)

• **Vertical cavity surface emitting laser transmitters for energy efficient broadband access networks**
  E. Wong, M. Mueller, M. P. I. Dias, C. A. Chan, and M.-C. Amann
  IEEE International Conference on Communications- Optical Networks and Systems, Ottawa, Canada (2012)

• **Voltage spectroscopy and the operating state of an optically injected long wavelength VCSEL**
  A. Daly, T. Gruendl, S. Huber, M. Mueller, B. Roycroft, M.-C. Amann, and B. Corbett
7. Invited Talks

Gerhard Abstreiter

1. *Arsenide Based Hetero-Nanowires–MBE growth, Optical and Electronic Properties*
   Winterschool Mauterndorf, Austria (16.02.2012)

2. *Si based nanophotonics/nanoelectronics*

3. *Optical Control of Spins in Quantum Dots*
   Kolloquium, NRC, Ottawa, Canada (30.04.2012)

4. *Optical Properties of Semiconductor Quantum Dots and Hetero-Nanowires*
   Lecture, Ottawa Nanophotonics Summer School, Canada (01.05.2012)

5. *Optical Control of Spins in Quantum Dots*
   Plenary Talk, 20th Int. Symp. on Nanostructures, Wolga, Russia (28.06.2012)

6. *Molecular Beam Epitaxy*
   Seminar, MBE Komponenten GmbH, Weil der Stadt, Germany (31.08.2012)

7. *Ultrafast Optical Control of Spins in Coupled Quantum Dots*
   Invited Talk, CeNS-Venedig, Italy (20.09.2012)

Markus-Christian Amann

1. *Advanced concepts for single-mode and tunable semiconductor lasers for the near to far infrared*
   International Nano-Optoelectronics Workshop (iNOW), Berkeley & Stanford, USA (13.08.2012)

2. *Tunable lasers from telecom to optical sensing*
   International Symposium for 40th Anniversary of Single-Mode Semiconductor Lasers, Tokyo, Japan (06.11.2012)

Martin S. Brandt

1. *Donors for quantum computation*
   Colloquium, Universität Dortmund, Germany (17.04.2012)

2. *Pulsed electrically detected magnetic resonance at the Si/SiO2 interface*
   IOP Silicon Quantum Information Processing Meeting, University of Warwick, Coventry, UK (14.09.2012)
3. *Thermoelectrics*  
   MATCON Summer School, Prague, Czech Republic (04.10.2012)

Jonathan Finley

1. *Semiconductor based quantum optical nanosystems*  
   Colloquium, Max Planck Institut für Quantenoptik, Garching, Germany (31.01.2012)

2. *Hybrid electro-optical quantum nanosystems*  
   Invited Talk, Interfacing solid-state quantum information processing systems  
   (21.02.2012)

3. *Semiconductor based quantum nanosystems*  
   Invited Seminar, Mesa+ Institute Seminar, U. Twente, Netherlands (13.03.2012)

4. *Semiconductor based quantum optical nanosystems*  
   Invited Seminar, Tyndall National Institute, Cork, Ireland (27.03.2012)

5. *All optical preparation, storage and readout of a single spin in an electrically switchable self-assembled quantum dot*  
   Contributed Talk, QD-2012, Santa-Fe, USA (18.05.2012)

6. *Optically probing charge and spin dynamics in single and coupled quantum dots*  
   Invited Talk, ICPS 2012, Zürich, Switzerland (30.07.2012)

7. *The Nanosystems Initiative Munich*  
   Invited Talk, NIM GP Summer Retreat, Garmisch Partenkirchen, Germany  
   (13.06.2012)

8. *Optically probing charge and spin dynamics in single and coupled quantum dots*  
   Invited Talk, ICPS 2012, Zürich, Switzerland (30.07.2012)

9. *Semiconductor based quantum optical nanosystems*  
   Invited Colloquium, Joint Quantum Institute, U. Maryland, MD, USA (15.10.2012)

10. *Optically probing charge and spin dynamics in single and coupled quantum dots*  
    Invited Colloquium, NIST Gaithersburg, Maryland, USA (16.10.2012)

11. *Ultrafast control of spin in quantum dots and molecules*  
    Invited Colloquium, Naval Research Labs, Washington DC, USA (17.10.2012)

12. *Semiconductor quantum optical nanosystems*  
    Colloquium, Massachusetts Institute of Technology, Boston, USA (18.10.2012)

13. *Semiconductor based quantum optical nanosystems*  
    Colloquium, Stanford University, Palo Alto, CA, USA (22.10.2012)

14. *Semiconductor based quantum optical nanosystems*  
    University of California, Berkeley, CA, USA (24.10.2012)
15. **Ultrafast optical control of spin in quantum dot nanostructures**  
Invited Colloquium, EPFL, Switzerland (27.11.2012)

16. **Ultrafast optical control of spin in artificial atoms and molecules**  
Invited Talk, S3-Nano Kick Off Meeting, Munich, Germany (15.12.2012)

**José Garrido**

1. *Graphene: a novel carbon material for sensing applications*  
European Materials Research Society (E-MRS), Strasbourg, France (14.05.2012)

2. *Graphene sensors for Bioelectronics*  
Materialforschungstag Mittelhessen 2012, Philipps-Universität Marburg, Marburg, Germany (10.05.2012)

3. *Graphene Field Effect Transistors for Bioelectronics*  
CIMTEC, Montecatini Terme, Italy (13.06.2012)

4. *Graphene Field Effect Transistors for Bioelectronics*  
University of Applied Sciences, Kaiserslautern, Germany (27.06.2012)

5. *Electrical interfacing of cells with graphene field effect transistors*  
Center for Nanoscience and Technology, Istituto Italiano di Tecnologia (IIT), Milan, Italy (03.12.2012)

**Thomas Grange**

1. *Quantum cascade lasers made of nanowire superlattices*  
International Conference on Superlattices, Nanostructures and Nanodevices, Dresden, Germany (26.07.2012)

**Christian Grasse**

1. *GaSb- and InP-based devices for mid-infrared gas sensing application*  
2nd International Workshop on Opportunities and Challenges in Mid-Infrared Laser-Based Gas Sensing (MIRSENS2), Wroclaw, Poland (18.10.2012)

**Tobias Gründl**

1. *Long-wavelength VCSELs for sensing applications*  
Photonics West, San Francisco, USA (23.01.2012)

2. *New standards in high-speed and tunable long wavelength VCSELs*  
Photonics Europe, Semiconductor Lasers and Laser Dynamics, Brussels, Belgium (17.04.2012)

3. *Recent results on long-wavelength VCSELs: Device structures, performance and applications*  
IEEE Photonics Conference (IPC), San Francisco, USA (24.09.2012)
Moritz Hauf

1. *Controlling the charge state of nitrogen-vacancy centers*
   Summerschool 2012, Ion implantation for quantum application RUBION, Ruhr-Universität Bochum, Germany (30.08.2012)

Alexander Holleitner

1. *Picosecond photocurrents and THz generation in graphene*
   IOP Workshop on Frontiers of Dirac Electron Systems, Institute of Physik (IOP) Beijing, PRC (05.01.2012)

2. *Picosecond photocurrents and THz generation in graphene*
   17th International Winterschool on New Developments in Solid State Physics, Mauterndorf, Germany (16.02.2012)

3. *Picosecond photocurrents and THz generation in nanoscale circuits*
   Junior Nanotech Network (JNN), Wolfgang Hillen Summer School, University of California, Santa Barbara, USA (27.03.2012)

4. *Picosecond photocurrents and THz generation in nanoscale circuits*
   Physik-Kolloquium, Universität Paderborn, Germany (09.05.2012)

5. *Picosecond photocurrents and THz generation in nanoscale circuits*
   Gruppen-Seminar, Max-Planck Gruppe für strukturelle Dynamik, Hamburg, Germany (11.06.2012)

6. *Picosecond photocurrents and THz generation in nanoscale circuits*
   Physik-Kolloquium, Complex Quantum System (CoQuS), TU Wien, Austria (18.06.2012)

7. *Resonant photoconductance of molecular junctions formed in Gold nano-particle arrays and Coulomb-blockade phenomena*
   International workshop on “Ordered and non-ordered superstructures of nanosized objects” (ONSNO), Max-Planck-Institut für Physik komplexer Systeme, Dresden, Germany (13.07.2012)

8. Nanotechnologien erleben
   Alumni-Tag TUM, TUM, Garching, Germany (30.11.2012)

Gregor Koblmüller

1. *III-V nanowire arrays on Silicon: Growth, material properties and prospects for heterojunction devices*
   UC Santa Barbara, Materials Department, SSLEC Seminar, Santa Barbara, USA (13.04.2012)

2. *III-V semiconductor nanowire arrays on Silicon: Growth, material properties and prospects for heterojunction devices*
   TU Wien, Institute of Solid State Electronics, FKE Seminar, Wien, Austria (08.05.2012)
3. *Growth and properties of In(Ga)As core, InAs-GaAs and InAs-InAsP core-shell nanowires on Si*
   TU Dresden, Inst. of Structure Physics, Seminar, Dresden, Germany (25.07.2012)

4. *Growth and properties of InAs core, InAs-GaAs and InAs-InAsP core-shell nanowires on Si (111)*
   31st Int’l Conf. Physics of Semiconductors (ICPS), Zürich, Switzerland (03.08.2012)

5. *(In,Ga)As based nanowires on Si: Growth, material properties and prospects for heterojunction tunneling devices*
   Seminar in University of Notre Dame, Dept. of Electrical Engineering, South Bend, Indiana, USA (04.09.2012)

6. *(In,Ga)As based nanowires on Si: Growth, material properties and prospects for heterojunction tunneling devices*
   Northwestern University, Materials Science and Engineering Dept., MRSEC Seminar, Evanston/Chicago, USA (07.09.2012)

7. *Growth and optical properties of (In,Ga)As nanowire arrays on Silicon*
   Nanowires-12, Berlin, Germany (20.09.2012)

**Kai Müller**

1. *Probing ultrafast charge and spin dynamics in an InGaAs quantum dot molecule*
   Photonics West Conference, San Francisco, USA (22.01.2012)

2. *Probing ultrafast charge and spin dynamics in an InGaAs quantum dot molecule*
   Seminar, University of California, Merced, USA (27.01.2012)

3. *Probing ultrafast charge and spin dynamics in an InGaAs quantum dot molecule*
   Seminar, University of New South Wales, Australia (23.02.2012)

4. *Probing ultrafast charge and spin dynamics in single self-assembled quantum dots and molecules*
   Seminar, Universität Augsburg, Germany (24.10.2012)

**Michael Müller**

1. *InP-based 1.3 µm and 1.55 µm short-cavity VCSELs suitable for telecom- and datacom applications*
   14th International Conference on Transparent Optical Networks (ICTON), Warwick, England (02.07.2012)

**Günther Reithmaier**

1. *Towards On-Chip Quantum Optics using Superconducting Single Photon Detectors coupled to Photonic Crystal Waveguides*
   76th Annual Conference of the DPG, TU Berlin, Berlin, Germany (29.03.2012)
Fabian Schuster

1. *Nitrides and Oxides on diamond – Challenges and Opportunities*
   Diamond Workshop SBDD XVIII, Hasselt, Belgium (01.03.2013)

Friedrich Simmel

1. *Synthetic transcription networks and DNA nanodevices*
   Workshop in Honor of Nadrian Seeman on "DNA Nanotechnology: From Structure to Function", Shanghai, China (03/2012)

2. *Controlling the Motion of DNA Nanodevices with an Artificial Transcriptional Clock*
   MRS, San Francisco, USA (05/2012)

3. *Rational assembly of functional nanostructures using DNA origami*
   E-MRS, Strasbourg, France (05/2012)

4. *Driving DNA nanodevices with in vitro transcription circuits*
   CIMTEC 2012, Montecatini Terme, Italy (06/2012)

5. *Assembly of functional nanostructures using DNA origami*
   Workshop on Concepts and Applications of Stimulus-Responsive Materials, San Sebastian, Spain (06/2012)

6. *DNA devices and circuits as components for cell-like microcompartments*
   DNATec 2012 (in conjunction with DAN 18), Aarhus, Denmark (08/2012)

Martin Stutzmann

   Werkstoffwissenschaftliches Kolloquium, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany (07.02.2012)

2. *Hybrid Organic/Inorganic Solar Cells with Silicon Nanoparticles*
   MRS Spring Meeting 2012, San Francisco, USA (10.04.2012)

3. *Catalysis with GaN*
   Joint Center for Artificial Photosynthesis, Berkeley, USA (13.04.2012)

4. *Hybrid Solar Cells*
   Workshop on Advanced concepts in silicon based photovoltaics, SINTEF, Oslo, Norway (20.06.2012)

Ruoshan Wei

1. *DNA Origami Gatekeepers for Solid-State Nanopores*
   Nanopores Conference 2012, Lanzarote, Spain (09.02.2012)
2. *Stochastic Sensing of Proteins with Receptor-Modified Solid-State Nanopores*
   Biophysical Society Annual Meeting, San Diego, USA (28.02.2012)

3. *Hybrid Solid-State Nanopores for Stochastic Sensing of Single Protein and DNA Molecules*
   Seminar Talk, University of California, Irvine, USA (03.03.2012)

**Andreas Wild**

1. *Development of SiGe heterostructures for applications in quantum information processing*
   Pinceton University, Pinceton, USA (05.03.2012)

2. *Development of SiGe heterostructures for applications in quantum information processing*
   IBM Research Center, Yorktown Heights, USA (06.03.2012)
8. Courses and Seminars

Markus-Christian Amann

WS 2011/12
Werkstoffe der Elektrotechnik
Technologie der III/V-Halbleiterbauelemente
(zusammen mit Ralf Meyer)
Optoelektronik II

SS 2012
Optoelektronik I (Optoelectronics I)
Optoelectronics
Hauptseminar Optoelektronik
(Advanced Seminar Optoelectronics)
Praktikum Optische Übertragungstechnik
(Practical Course Optical Transmission Technology)
(zusammen mit Prof. Erwin Biebl)

WS 2012/2013
Werkstoffe der Elektrotechnik (Materials for Electrical Engineering)
Technologie der III/V-Halbleiterbauelemente
(Technology of III/V Semiconductor Devices)
(Dr. Ralf Meyer)
Optoelektronik II (Optoelectronics II)

Martin S. Brandt

WS 2011/2012
Renewable Energies I
Seminar Aktuelle Probleme der Halbleiterphysik
Seminar zu aktuellen Fragen der Magneto- und Spintronik
(zusammen mit S. Gönnenwein und H. Hübl)

SS 2012
Renewable Energies II
Seminar zu Renewable Energies II

WS 2012/13
Halbleiterphysik
Hendrik Dietz

WS 2011/2012  Experimentalphysik I (MSE)
Seminar: Aktuelle Entwicklungen in der biomolekularen Nanotechnologie

SS 2012  Experimentalphysik II (MSE)
Seminar: Aktuelle Entwicklungen in der biomolekularen Nanotechnologie

WS 2012/2013  Experimentalphysik I (MSE)
Seminar: Aktuelle Entwicklungen in der biomolekularen Nanotechnologie

Jonathan Finley

WS 2011/2012  Introduction to solid-state physics

SS 2012  Materials physics

WS 2012/13  Sabbatical

José Garrido

WS 2011/2012  Biosensors and Bioelectronics I
Seminar zu „Biosensors and Bioelectronics I

SS 2012  Biosensors and Bioelectronics
NANO 301-1 Electronic Properties of Nanoengineered Materials (zusammen mit Prof. G. Abstreiter, Prof. M. Stutzmann und Prof. M. Grayson)

WS 2012/2013  Biosensors and Bioelectronics I
Seminar zu Biosensors and Bioelectronics I

Alexander Holleitner

WS 2011/2012  Experimentalphysik II für Lehramtskandidaten an den Berufsschulen (LB-Technik)
Nanosystems II (Physics of Organic Nanosystems)
Introduction to Nanoanalytics
(zusammen mit Dr. Helmut Oppolzer, Siemens AG)

SS 2012

Materialwissenschaften II
(zusammen mit Prof. Christian Große, Prof. Tom Nilges)

Nanosystems II

WS 2012/13

Materialwissenschaften I
(zusammen mit Prof. Christian Große, Prof. Tom Nilges)

Nanosystems I
(zusammen mit Dr. Eric Hoffmann)

Seminar zu Nanosystems I
(Dr. Anna Cattani-Scholz, Dr. Emanuela Margapoti)

Gregor Koblmüller

WS 2011/2012
Introduction to Nanofabrication and Nanoanalytics

SS 2012
Semiconductor Physics II – Physics of Low-dimensional Systems

WS 2012/2013
Introduction to Nanofabrication and Nanoanalytics

Emanuela Margapoti

WS 2011/2012
Nanosystems I - Seminar for Master Students

SS 2012
Plasmonics - Fundamentals and Applications

WS 2012/2013
Nanosystems I - Seminar for Bachelor Students
Nanosystems I - Seminar for Master Students

Friedrich Simmel

WS 2011/2012
Experimentalphysik 1
Bionanotechnologie
Forschungsseminar „Synthetische Biologie“

SS 2012
Experimentalphysik 2
Systembiophysik
Seminar zu Systembiophysik

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<td>Vorlesung: Physik der Nukleinsäuren und Anwendungen in der Bionanotechnologie</td>
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**Martin Stutzmann**

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**Peter Vogl**

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**Ilaria Zardo**

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Walter Schottky Seminars

**Processing diamond for devices towards neuro interfaces and implant fabrication**
Dr. Philippe Bergonzo, CEA-Saclay, France (24.01.2012)

**Tailor-made molecules in physical experiments**
Prof. Marcel Mayor, Department of Chemistry, University of Basel, Switzerland (31.01.2012)

**Electronic recombination at c-Si/a-Si:H interfaces: g-tensor calculations for (quasi-)metallic systems**
Dr. Uwe Gerstmann, Universität Paderborn, Germany (07.02.2012)

**(Al,Ga,In)N/GaN-based heterostructures: Physics and devices**
Dr. Patrick Waltereit, Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany (23.02.2012)

**Diamond nanophotonics**
Birgit Hausmann, Harvard University Cambridge, USA (12.03.2012)

**The role of surfaces in the electronic and optical properties of nanowires and nanowire heterostructures**
Dr. Yann-Michel Niquet, Institute for Nanosciences and Cryogenics (INAC), CEA Grenoble, France (13.03.2012)

**Efficiency of multi-exciton generation in colloidal nanostructures**
Dr. Alexander L. Efros, Naval Research Laboratory, Washington DC, USA (03.04.2012)

**Analysis and design of binary message passing decoders**
Prof. Gerhard Kramer, Lehrstuhl für Nachrichtentechnik TU München, Germany (24.04.2012)

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