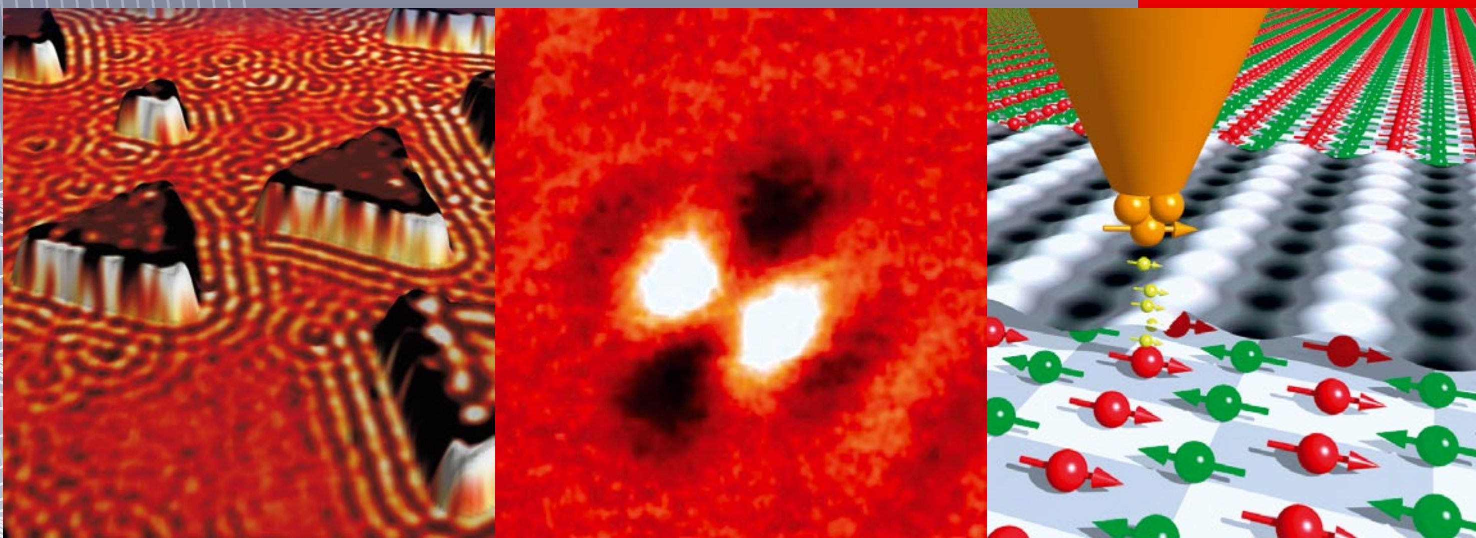
Center for Solid State and Nanostructure Physics



University of Hamburg

Impressum

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Preface

Within the past decades considerable progress has been made in the fabrication of nanometer-scale structures with unprecedented degree of control. Atomic layer epitaxy and molecular beam epitaxy allow the growth of heterostructures and multilayer systems with atomically defined interfaces. Scanning probe technology has led to the first controlled manipulation of matter at the atomic level providing new opportunities to synthesize and engineer materials and systems at the atomic scale. New analytical approaches to investigate nanometer-scale properties of matter have emerged, primarily based on scanning tunnelling microscopy/spectroscopy and related techniques. New nanometer-scale materials have been synthesized such as fullerenes, carbon nanotubes and silicon nanowires. New phenomena have been discovered based on the reduced dimensionality of the systems under investigation, such as the quantum Hall effect and giant magneto resistance. This emerging field of nanoscience and technology has major impact in several different disciplines: in physics with regard to the fundamental understanding of artificially-constructed material systems; in chemistry because of the unprecented degree of control in the synthesis of nanometer-scale structures with well defined geometrical, electronic and magnetic properties, and finally in biology where new analytical tools allow the detailed investigation of the structure-function-relationship at a subcellular level.

Nanoscience and nanotechnology will undoubtedly continue to lead to exciting scientific advances and challenges, and will simultaneously have enormous technological and societal impact similar to the present information technology revolution that resulted from the invention of the transistor and the subsequent development in microelectronics. It is the aim of the new Center for Solid State and Nanostructure Physics to continue making significant contributions to the exciting development in nanoscience and technology and to provide a Center of Competence for collaboration with other research institutions and industrial partners, particularly in the northern part of Germany.

Center for Solid State an

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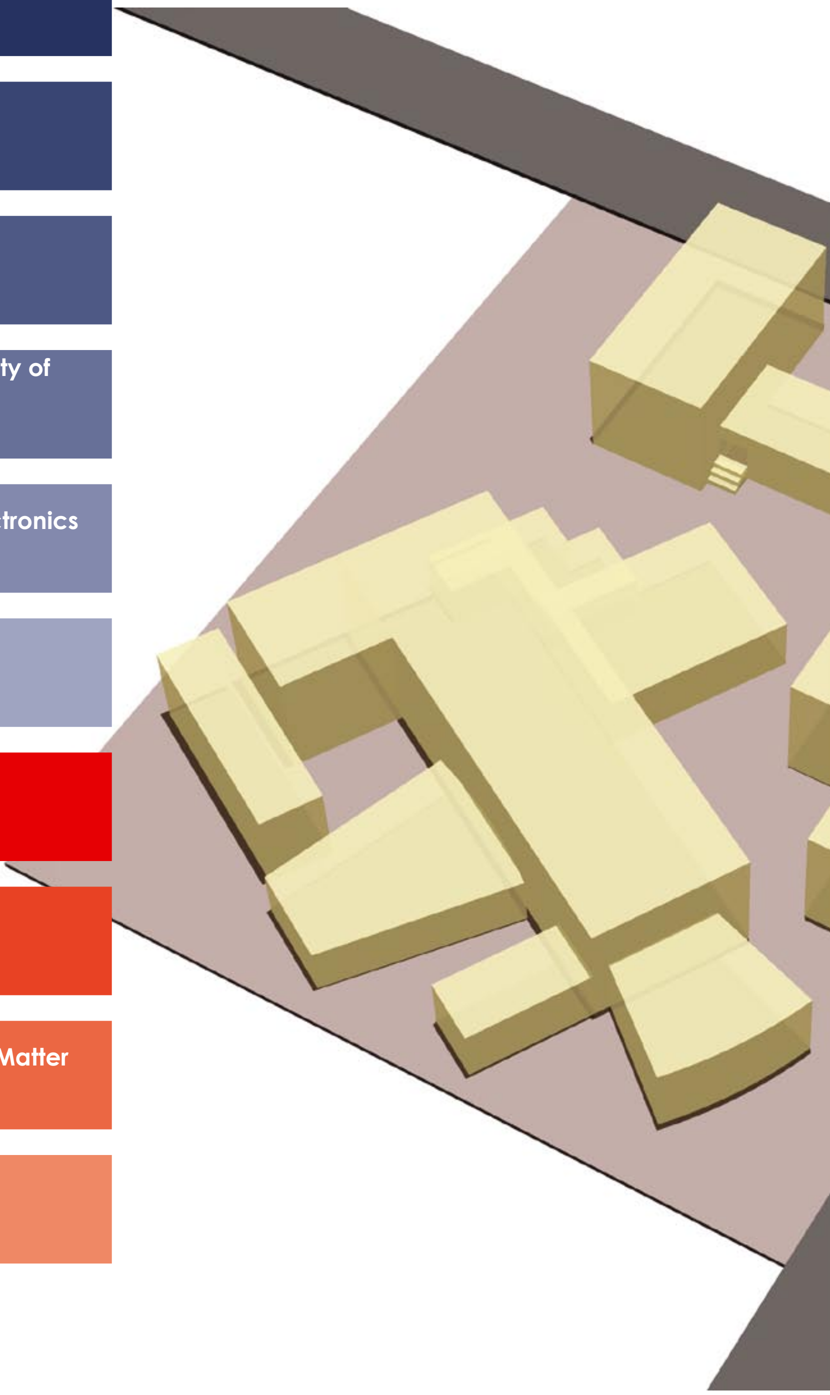
The Center for Solid State and Nanostructure Physics at Hamburg University was established in 2004 and comprises the Institute of Applied Physics, the Microstructure Advanced Research Center Hamburg (MARCH) and the I. Institute for Theoretical Physics.



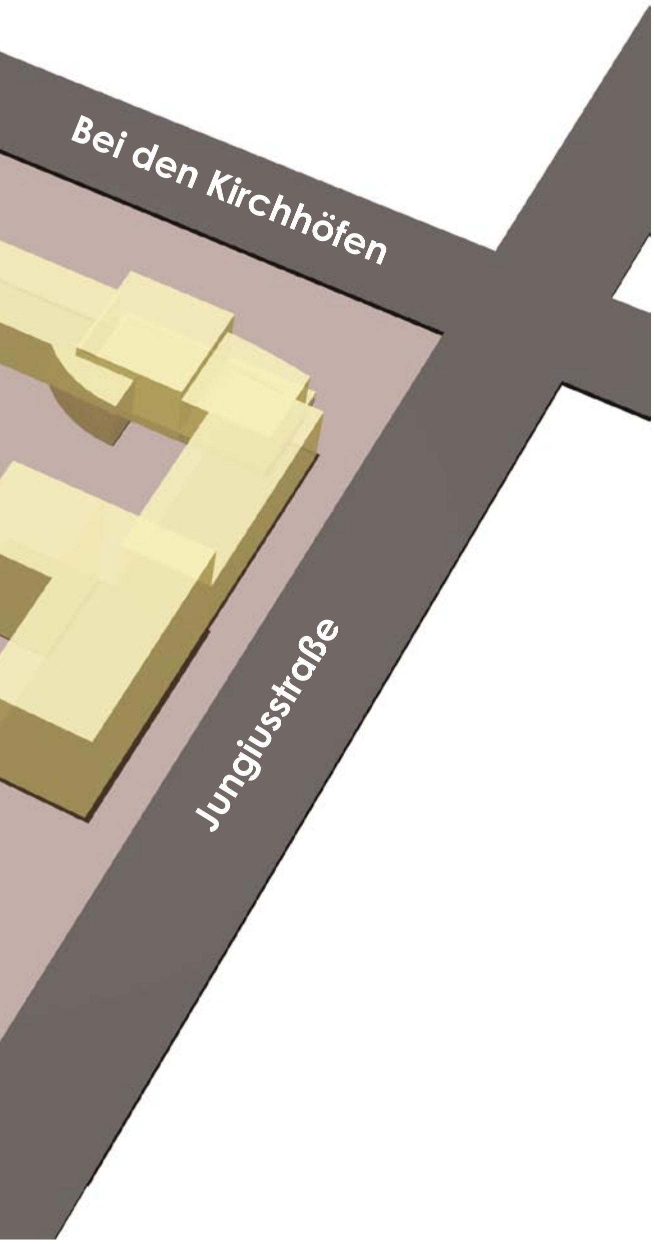
d Nanostructure Physics

Goals

The three major goals of the Center are

- research on an internationally competitive level,
- education of undergraduate and graduate students in topical fields of solid state and nanostructure physics, and
- technology transfer to local and national industry.

These three goals are closely related. The transfer of “hot” research results directly into the lecture halls and, on the other hand, the integration of young students with their new ideas and enthusiasm into current research projects is greatly facilitated by the incorporation of this Center into preexisting buildings of the university in the heart of the City of Hamburg.



Research

The fundamental research areas covered by the Center include semiconductor physics, nanostructure physics, scanning probe methods, surface and interface physics, magnetism and low temperature physics, as well as solid state theory. A close collaboration among the research groups of the Center exists for the fabrication as well as characterization of artificially micro- and nanostructured materials, including semiconductors, metals, superconductors and magnetic systems. Furthermore, the strong interaction between experiment, theory and computer simulation plays an important role for advances in the understanding of fundamental properties of micrometer- and nanometer-scale structured materials.

Education

The academic staff of the Center offers special education programs to undergraduate and graduate students covering topics related to the research areas described above, e.g. nanostructure physics, principles and applications of scanning probe methods, surface physics, low dimensional electron systems, or magnetism and superconductivity. Research is the fertilizing ground for high-level academic teaching which leads our students within challenging research projects to the forefront of international science.

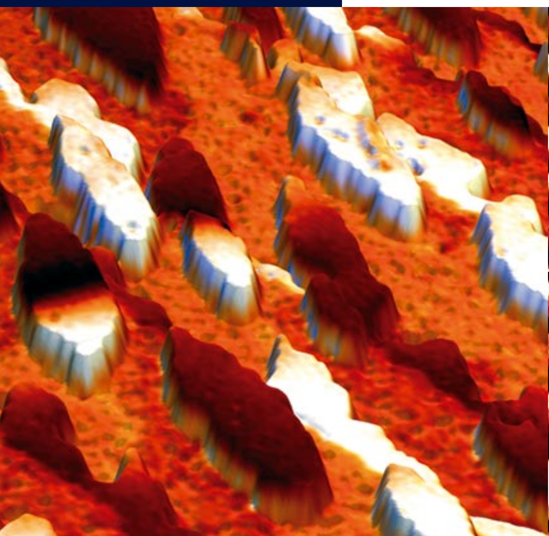
Collaboration

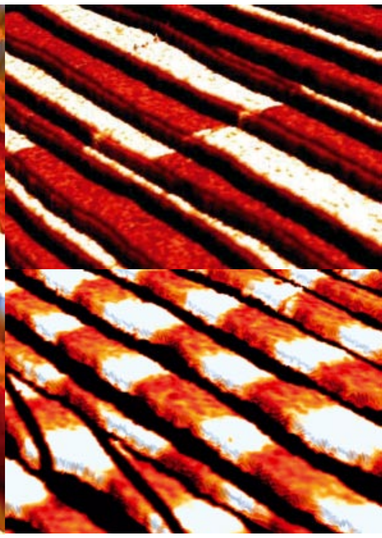
Collaborations with local and national industry, most often through joint research projects, is another focus area of the Center. The technology transfer is strengthened through exchange of personnel between the Center and industrial companies which proved to be important for turning academic research results into industrial applications.

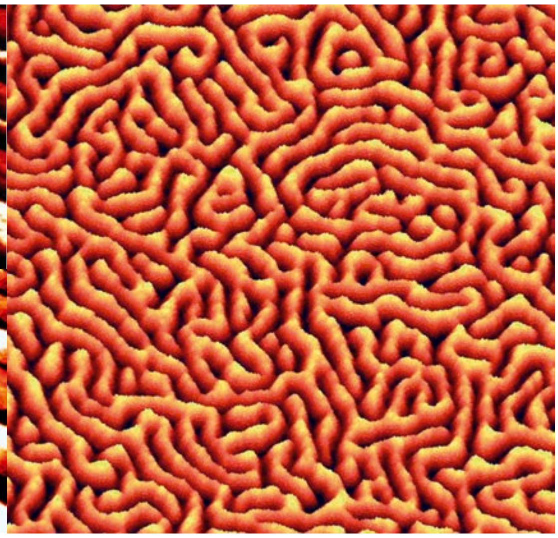
Scanning Probe Methods

Research Activities

Our research activities are concentrated on nanometer-scale science and technology based on scanning probe methods (SPM). In particular, we investigate the fundamental relationship between nanostructure and nanophysical properties. We apply scanning tunneling microscopy (STM) and spectroscopy (STS), atomic force microscopy (AFM), magnetic force microscopy (MFM) and other scanning probe methods to various classes of materials, including metals, semiconductors, insulators, superconductors, magnetic materials, molecular thin films, and biological systems. Laterally nanostructured materials are obtained by using SPM-based nanofabrication processes, which may be based on strong mechanical, electronical or magnetic interaction between probe tip and sample, as well as by using self-organization phenomena. Future nano-scale devices and ultrahigh density data storage systems are being developed in close collaboration with industry.







*Nano-scale magnetic Fe-islands (**left**) and Fe-wires (**middle**) grown on a stepped W(110) surface. The magnetization directions are color coded and have been determined by spin-polarized STM.*

***right:** Domain structures of a $La_{0.7}Sr_{0.3}MnO_3$ thin film visualized by magnetic force microscopy at low temperatures.*

STM/SPSTM on Magnetic Nanostructures

Nowadays, the use of topographic and spectroscopic modes of the scanning tunneling microscope (STM) almost routinely allows the correlation of local structural with electronic properties down to the atomic scale. By using a magnetic probe tip we have made the STM sensitive to the spin of the tunneling electrons. We can now measure both the in-plane as well as the out-of-plane magnetization component of the sample down to the atomic scale. The smallest magnetic features observed so far were atomically sharp domain walls in ferromagnetic iron films, the atomic scale antiferromagnetic structure of a manganese monolayer, and the spin-dependent electron scattering at single adsorbed atoms.

STM/SPSTM on Semiconductor Nanostructures

As model system for electronic states in semiconductors, we use the simple, isotropic and largely parabolic conduction band of InAs to study the influence of electron-disorder and electron-electron interactions on the appearance of the local density of states. Dimensionality and magnetic field are systematically varied, while electron density and the disorder potential are independently determined which gives full access to the input parameters of the Schrödinger equation. Since, on the other hand, the local density of states is directly linked to the output of the Schrödinger equation, we get access to the fascinating quantum world of interacting electrons.

Prof. Dr. Roland Wiesendanger

MFM on Magnetic and Superconducting Oxides

Magnetic force microscopy is used to probe magnetic phenomena in magnetic and superconducting oxides. Our research focuses on fundamental aspects of domain nucleation and growth as well as on vortex phases in high-temperature superconductor materials.

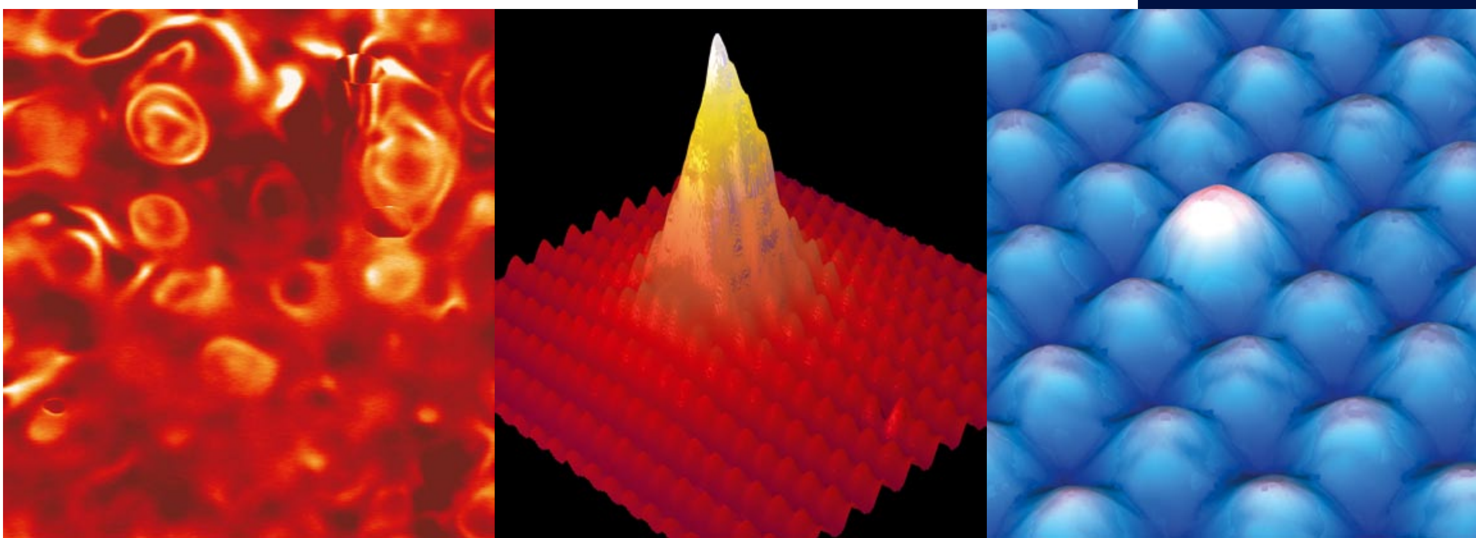
Currently, our most challenging scientific goal is the combination of MFM with the atomic resolution capability of atomic force microscopy (AFM) to perform exchange force microscopy, i.e., the detection of the exchange force between spins of individual surface atoms and a magetic atom at the tip end.

AFM on Insulators and Biological Systems

Atomic force microscopy is used to study well defined surfaces on the atomic scale. Besides true atomic resolution in the non-contact mode, the distance dependence of the forces on specific atomic sites is of particular interest for us. Nanometer- and even atomic-scale imaging on a variety of different samples has been achieved. On biological systems, however, the resolution is often limited by the intrinsic softness of organic materials. This drawback can be overcome by using samples which have been immobilized by cryo-techniques. For this purpose, we developed a non-contact scanning force microscope specially suited for the investigation of soft biological matter at low temperatures.

Theory of AFM and Nanotribology

Our research activities also concentrate on the investigation of the basic contrast mechanisms of atomic force microscopy (AFM) in non-contact and contact mode. This latter issue is strongly correlated to the field of nanotribology. We used the modified Tomlinson model to simulate experimental atomic force microscope images and demonstrated that the imaging capabilities of an AFM are mostly limited by the stick-slip movement of the tip on the sample surface.



left: *Magnetic field induced localization in the extreme quantum limit.* ***middle:*** *The STM-signal of an individual sub-surface dopant in an InAs-crystal.* ***right:*** *Atomic resolution with a non-contact scanning force microscope: an impurity in a NiO-crystal.*

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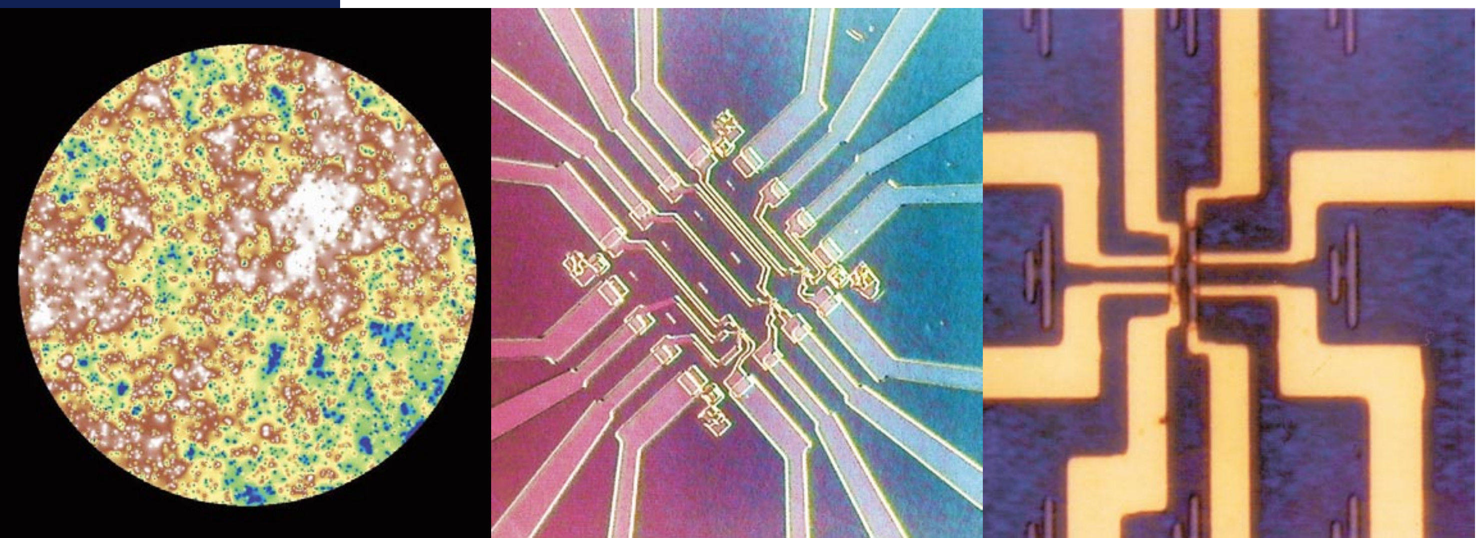
Nanostructure Physics

The research in our group focusses on semiconductors, hybrid semiconductor/metal structures, and ferromagnets on the micro- and nanometer scale.

As for semiconductors, magnetotransport experiments at low temperatures are performed on two-dimensional electron systems of Be-δ-doped GaAs/GaAlAs heterostructures, in order to study the influence of disorder on the quantum Hall effect and to reveal the nature of the metal-insulator transition in high magnetic fields.

In hybrid semiconductor/metal nanostructures a low-dimensional electron system in a semiconductor channel is made „superconducting“ or „magnetic“ through the close proximity of a superconductor like niobium or a ferromagnet like permalloy, respectively. These metals act as source and drain contacts for Andreev reflected or spin-polarized carriers. Close proximity means both, semiconductor/metal interfaces of extremely high quality, that display high electron transparencies and spin-injection rates, as well as short channel lengths, that are less than the superconductivity or spin-related coherence lengths. Since InAs does not form Schottky barriers to metals, it is the semiconductor of choice. InAs-based high-electron mobility transistors are obtained from the research group „Epitaxial Nanostructures“. The narrow channels between the source and drain contacts are patterned by electron-beam lithography and lift-off techniques, the gross features of the contact geometries are defined by conventional photolithography. Based on the hybrid quantum structures, Josephson field-effect transistors and spin transistor structures are prepared and examined in our group. The simultaneous control of the electron spin and charge is still in its infancy and quite a few obstacles have to be surmounted.



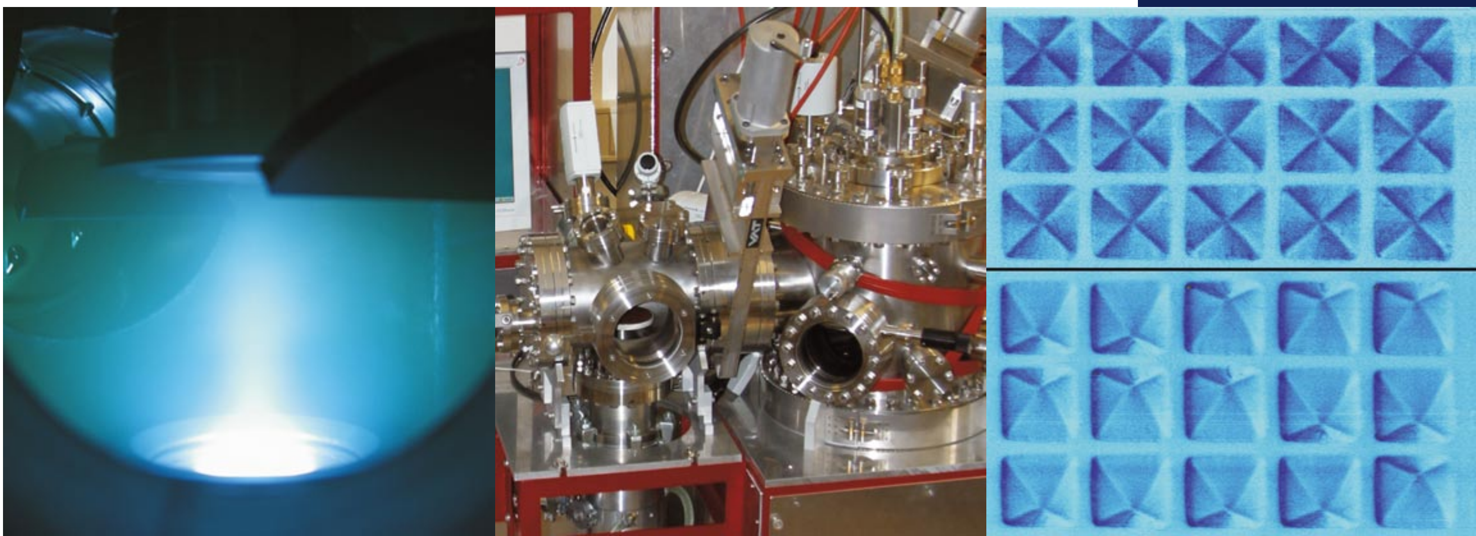
left: *Calculated potential landscape with positive and negative Coulomb scatterers in the plane of a two-dimensional electron system.* ***middle:*** *Twelve spin-transistor structures with permalloy source and drain contacts. Three of them are wired.* ***right:*** *Nine spin-valves on an InAs/GaAs heterostructure. They consist of permalloy pairs, one of them is contacted.*

In terms of spintronic devices, we focus on the formation of ferromagnetic domains, the dynamics of magnetization reversals and the electron transport in ferromagnetic nanostructures. Results from magnetic-force microscopy are compared with micromagnetic simulations.

Prof. Dr. Ulrich Merkt

Technologies for Preparation and Analysis

Our group is responsible for the general operation of the clean room and its equipment that is shared with the other groups. In particular, we take care of the systems for optical-mask and electron-beam lithography that are installed in the clean room. Together with the Mechanic and the Electronic Workshop we have implemented two ultra-high vacuum systems for magnetron sputtering and in situ cleaning of surfaces. One system is used for the deposition of the superconductor niobium, whereas the second is used for the ferromagnets iron and permalloy. High-quality niobium films and clean interfaces to quasi two-dimensional electron systems in InAs yield Josephson field-effect transistors with unprecedented figures of merit. Iron and permalloy electrodes serve as spin-polarized source and drain contacts in spin-transistor and spin-valve devices. Oxidized aluminum layers are employed as barriers in tunneling structures. By thermal evaporation we achieve structurally ordered, stoichiometric films of the Heusler alloy Ni_2MnIn. This half-metallic ferromagnet is predicted to retain its fully spin-polarized electron system at epitaxially grown interfaces to InAs. The topology, morphology, lattice structure, and chemical composition of thin films and laterally patterned nanostructures are examined by analytical methods like atomic-force (AFM) and magnetic-force (MFM) microscopy, scanning-electron (SEM) and transmission-electron (TEM) microscopy, X-ray and electron diffraction as well as energy dispersive X-ray analysis (EDX). The spin polarization of ferromagnetic thin films is determined by point-contact Andreev reflection (PCAR).



left: *View into the magnetron-sputtering chamber. An argon plasma is glowing above a permalloy target.* ***middle:*** *Magnetron-sputtering plant for ferromagnets, aluminum and copper.* ***right:*** *Symmetric Landau magnetization patterns in permalloy squares (top part) and shift in an external magnetic field (bottom part).*

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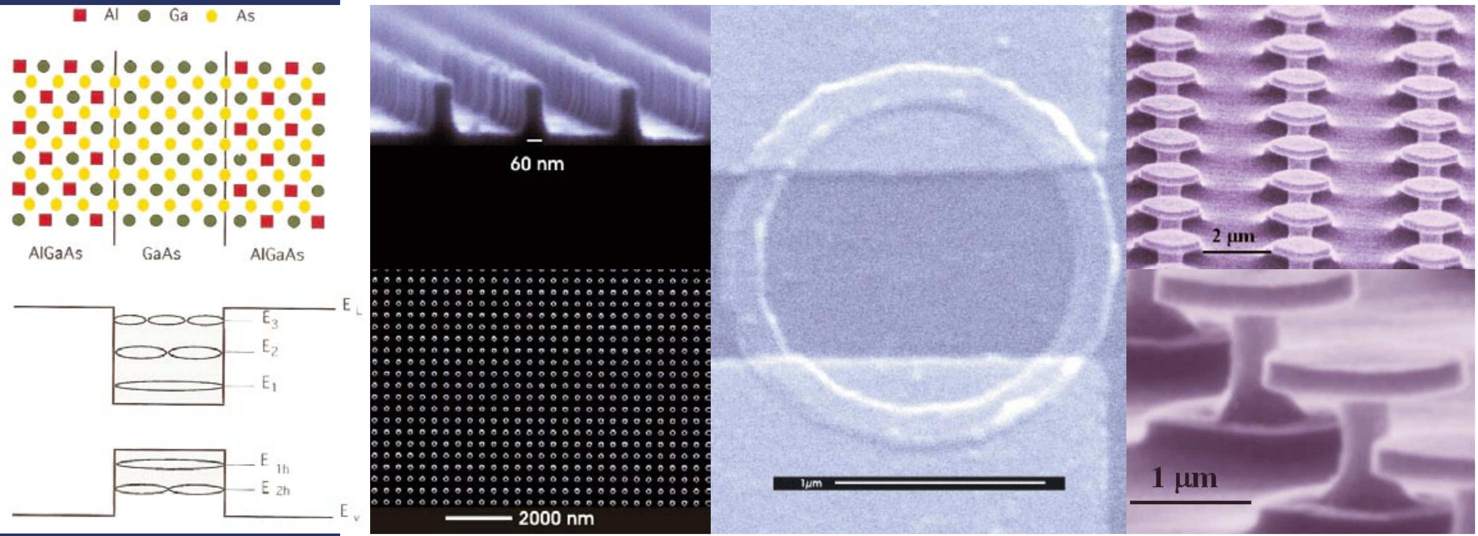
Semiconductor Physics

Research Activities

The research group Semiconductor Physics works intensively on III-V semiconductor systems for basic research and applications. Using molecular beam epitaxy (MBE), it is possible to grow alternating layers of, for example, GaAs and AlGaAs with well controlled thickness. A thin GaAs layer between two AlGaAs layers forms a potential well with quantized energy levels, both for electrons and holes. In these so-called quantum wells, electrons can still move freely within the plane of the layers and are thus called "two-dimensional electron system" (2DES). The goal of the Semiconductor Group is to go to even smaller dimensions and to realize 1DES and 0DES. Using sophisticated technology, it is possible to fabricate very narrow quantum wires with lateral width below 100 nm. Here the electrons can move freely only in one direction. Ultimately one can prepare quantum dots, where the electrons are completely quantized in all three dimensions, leading to discrete energies analogous to atomic energy levels. Due to the Coulomb blockade we can control



__left:__ Sketch of a quantum well. A layered AlGaAs-GaAs-AlGaAs system quantizes the energy levels of the electrons and holes. __inner left:__ Quantum dots and wires prepared by holographic lithography and dry etching. __inner right:__ Ferromagnetic ring with contacts. __right:__ GaAs micro disks, standing on thin pillars, support whispering gallery modes and exhibit optically pumped lasing.

the transfer of single electrons, N = 1, 2, 3 ..., into the dot. This allows us to perform a kind of atomic spectroscopy on these artificially created atoms. The most interesting aspect of these semiconductor microstructures is the possibility to tailor the physical properties of the device by the preparation and to control them by means of external electric and magnetic fields. In this way one can realize very specific systems and study various types of interactions as well as totally new physical phenomena. In recent years we have extended our research also on semimagnetic and metallic ferromagnetic nanostructures. The combination of semiconductors and ferromagnets opens the field of spintronics, i.e., the direct control of the spin.

Technologies

An essential idea of the group is that both, technology and experiments, can be done within the group. If possible, a sample is prepared and experimentally investigated by the same Master or PhD student. The close and immediate feedback between technology and experiments allows one to optimize these novel nanostructured systems, which present the forefront of modern semiconductor research. The lateral nanostructures are prepared starting from AlGaAs or InAs heterostructure wafers. We fabricate masks by e-beam, AFM, or holographic lithography. The latter method allows one to realize large arrays of up to 10^4 quantum wires or 10^8 quantum dots with excellent homogeneity. The mask pattern can be transferred into the semiconductors by etching techniques.

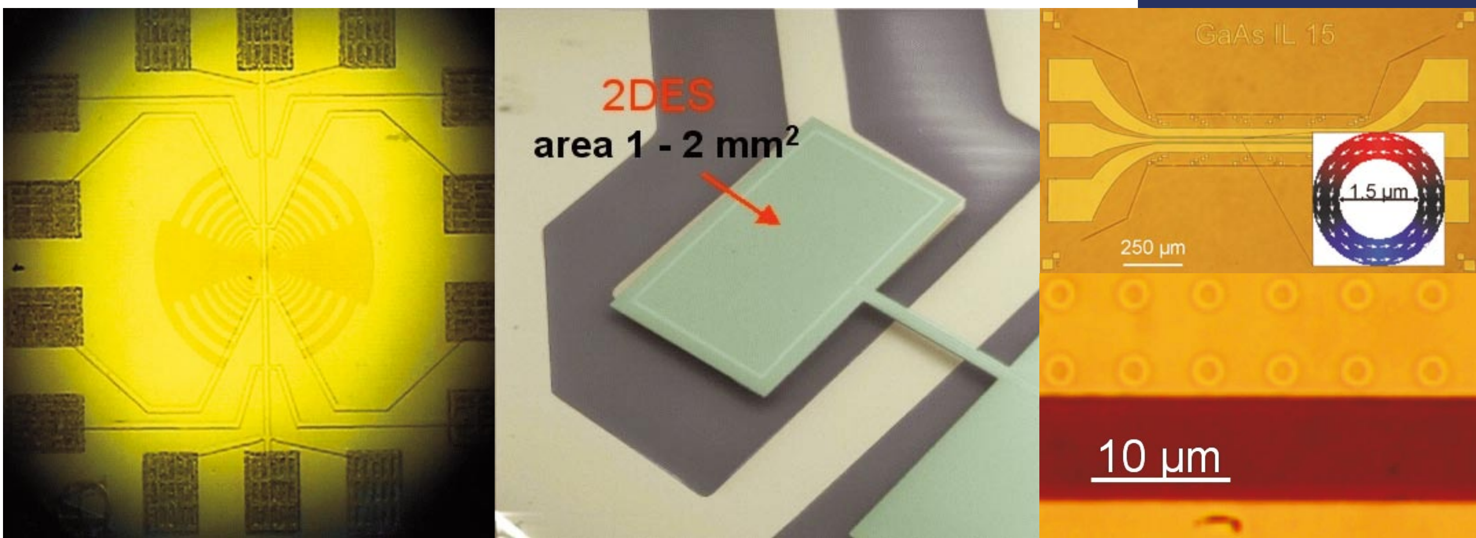
Prof. Dr. Detlef Heitmann

Experiments

Rapid-scan Fourier-transform spectrometers cover the frequency range from the far infrared (FIR) to the visible regime. Through FIR spectroscopy we can directly measure the energy levels in quantum systems. We have also established the very sensitive technique of FIR photoconductivity, which allows us to study combined spin-cyclotron resonances and to map the spin dependent density of states. A complementary experiment is Raman spectroscopy. Other powerful techniques are static and time-resolved photoluminescence (PL). For doped systems we get information about the density of states and can study charged excitons. A micro-PL set up allows single-dot spectroscopy. We also investigate transport and magnetization in semiconducting, superconducting, and ferromagnetic nanostructures. We have developed micromechanical cantilever magnetometers to study the magnetic properties of low-dimensional electron systems with high sensitivity. Other materials are deposited by flip-chip processes onto the cantilever. Dynamics in ferromagnetic nanostructures are studied in the frequency domain up to 80 GHz and in time domain down to the ps time scale.

Applications

Semiconducting nanostructures have a great potential for novel devices which utilize the tailored and tunable quantized energy levels and the peaked density of states in 1D and 0D. Electro-optical devices, for example lasers relying on quantum dots and whispering gallery modes are already in use and offer further promising applications in future. Our FIR photoconductivity measurements and work on the spin-orbit interaction is important for the new field of spintronics. The photoconductivity of quantum Hall states and of quantum wells and dots is the basis of infrared photo detectors. The investigation of nanomagnets and their dynamics is very interesting for novel non-volatile memories and ultrafast storage.



left: *Antenna structure for focussing far infrared light onto a single quantum wire for photo current spectroscopy.* ***middle:*** *Micromechanical cantilever with integrated 2D electron systems supported by a 5 µm thin and 100 µm wide beam.* ***right:*** *Coplanar waveguide containing ferromagnetic nanorings for studies of the magnetization dynamics.*

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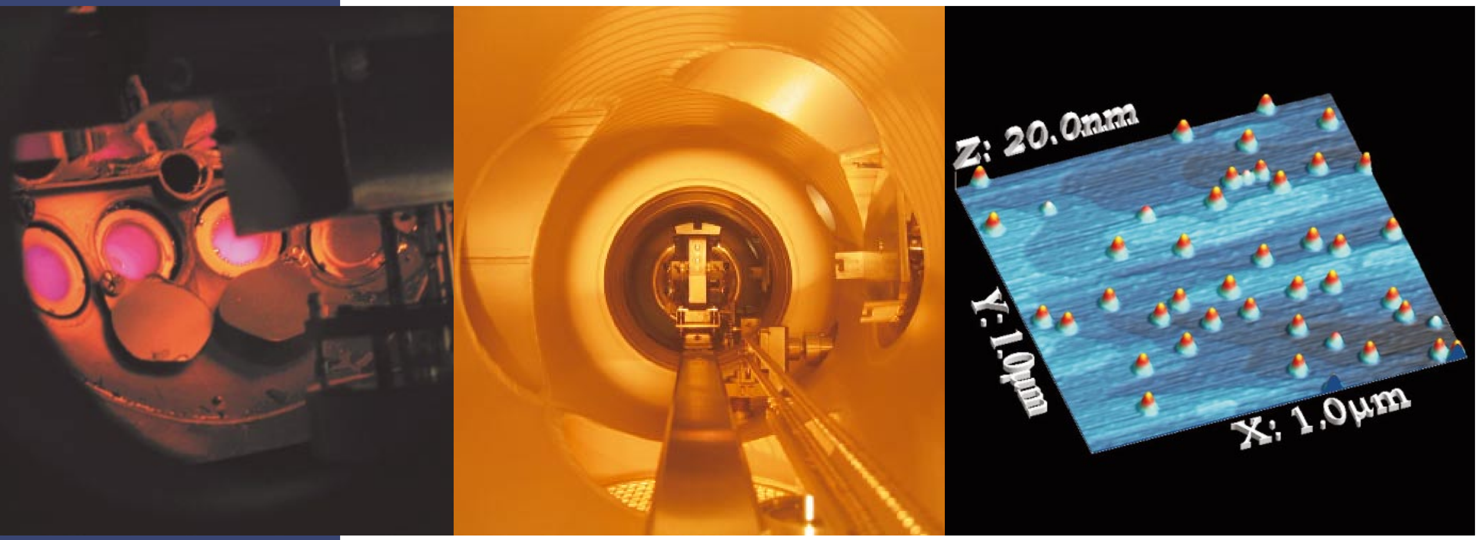
Epitaxial Nanostructures

Research Activities

In the semiconductor epitaxy group, heterostructure crystals with tailored electro-optical properties are prepared and investigated. Confinement of electrons into artificial potentials on the nanometer scale is employed to reveal and exploit quantum effects.

With the solid source molecular beam epitaxy (MBE) systems, operated in this research group, extremely high purity semiconductor layers of altering composition are deposited with atomic precision. Such semiconductor heterostructures are of high technological interest as well as of central importance for fundamental research. On the one hand they are the basis of many modern semiconductor devices like quantum-well lasers and heterojunction transistors. On the other hand the precise control of chemical composition, doping and thickness of the semiconductor layers as well as the high purity of the structures allow for the preparation of low-dimensional electron systems in artificial band structures where quantum effects play a crucial role.

At present the MBE growth chamber is equipped with Indium, Gallium, Aluminium and Arsenic cells for the growth of III-V compound semiconductors. Quasi-free electron systems are generated by modulation doping with Silicon. In the expitaxy group the remarkable fundamental physical properties of two-, one and zero-dimensional electron systems are studied by means of magneto-transport studies. Several liquid-Helium cryostats as well as set-ups for high-sensitivity capacitance measurements, admittance measurements, deep level transient spectroscopy and Hall-effect measurements are available. Furthermore, in order to reveal faint quantum effects a mixing chamber cryostat is operated in the research group for measurements at low-temperatures down to 20 mK and magnetic fields up to 16 T. For crystal surface inspection and manipulation two scanning probe microscopes are available.



left: *View into the MBE growth chamber. The purple glowing crucibles are the ovens containing the elementary materials.* ***middle:*** *View into the UHV-transfer chamber of the MBE facility.* ***right:*** *AFM-image of MBE-grown InAs-quantum dots deposited on a GaAs(100) crystal surface.*

Quantum wires, dots and rings

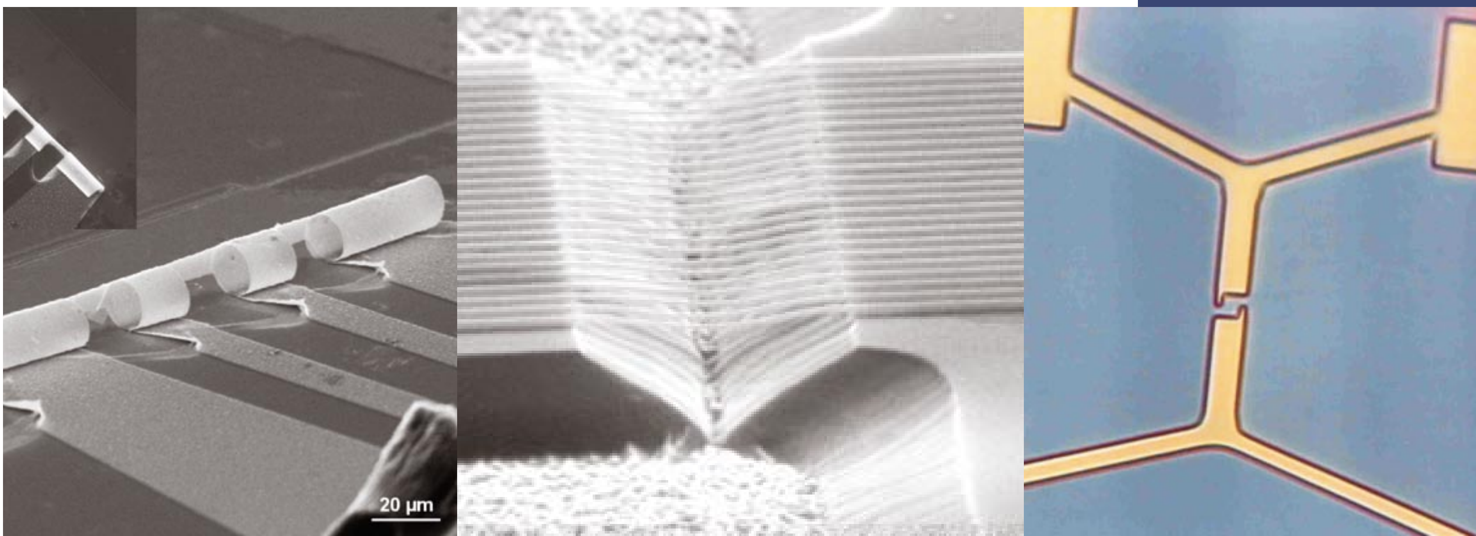
Quantum wires and dots are discussed as fundamental entities for novel data processing technologies such as quantum computation and spintronic devices. These waveguide or atomic like entities are presently already employed in communication technology for laser applications and in research laboratories for specific applications such as extremely sensitive charge detectors or single photon emitters. At present the major challenge is to built and investigate the rich physics of more complex molecular-like structures. In the epitaxy group both conventional semiconductor technology as well as novel approaches such as self-assembling mechanisms and manipulation by scanning

Prof. Dr. Wolfgang Hansen

probe microscopes are employed to fabricate such structures. E. g., when InAs is grown on GaAs the strain originating from the lattice mismatch leads to InAs-droplet formation that can be utilized for the fabrication of nanometer-size quantum dots embedded in a GaAs matrix. Aside from the structural and electronic properties we develop methods to control the location where growth of these self-assembled dots starts.

InAs-related heterostructures

Two important properties make the low band-gap material InAs distinct: The conduction-band electrons sense a strong spin-orbit coupling and the material develops a vanishing Schottky barrier when brought into contact with metals. These properties make the material promising for applications in novel spintronic devices. We fabricate high-mobility InAs-based heterostructures and study the effect of spin-orbit coupling on the transport properties of transistor-like devices.



left: *Semiconductor roll containing a two-dimensional electron system. Light grey stripes are metal pads supplying electrical contacts to the system.* ***middle:*** *Free-standing wire bridges that contact gate electrodes of quantum wire devices for capacitance measurements.* ***right:*** *Semiconductor GaInAs-heterostructure device containing an electron corral of 1 µm diameter between the 2D electron systems.*

Nanomechanical systems and nanorolls

Aside from the self-assembling dot formation the strain stored in GaAs-InAs heterojunctions can also be employed for the formation of curved layer systems. Free standing epitaxial layer structures are fabricated after MBE deposition by selective etching of a sacrificial layer. Novel devices like micrometer sized semiconductor coils and nanorolls containing quantum wells with a two-dimensional electron system are studied. The free-standing layers, only a few nanometers thick, can easily be bent mechanically by thermal expansion or electric fields. Novel sensor and actuator applications of such nanorolls are investigated.

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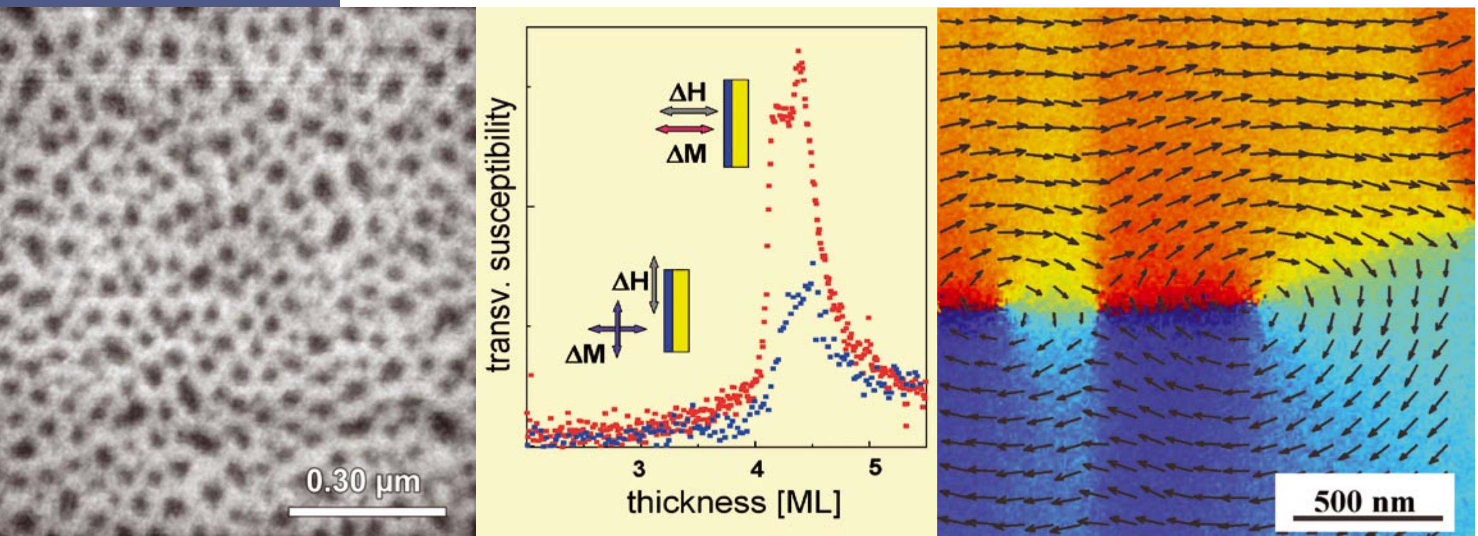
Surface and Interface Physics

Research Activities

The focus of our research is the magnetism in systems of reduced dimensions. Utilizing the experience and knowledge from surface science new artificial systems like, e.g., ultrathin films are created. The scope of our research is to study the influence of structure, strain, and surface/interface effects on the magnetic behavior. These effects are most pronounced in the ultrathin film limit. Basically, we start from single crystal substrates with perfectly prepared and known surface structure and stabilize thin films that are thermodynamically unstable.

In a second research effort we focus on the fabrication of laterally confined systems with thickness ranging from a monolayer (ML) to some 10 nanometers (nm). Again surface science techniques are utilized to create nanostructures. On special templates and with appropriate tuning of the growth conditions three dimensional growth can be triggered. Alternatively we use surfaces with stable nanoscale morphology, like microfacets. Evaporating material under oblique incidence leads to nanostructures with a lateral confinement defined by the template.



left: *Antidot array in a Pt film on Si. The silicon was covered by micelles. The micelles covered Si surface was then coated by a platinum film and sputtered under glancing incidence (1 KeV Ar+ ions). The ion bombardment removes the Pt on top of the micelles while the organic spheres prevent the Pt film in between to be removed.* ***middle:*** *Magnetic susceptibility of a Co/Au(111) thin film. The susceptibility was obtained during growth of the film and exhibits a spin reorientation transition with increasing film thickness. Two different Kerr signals have been obtained depending on the orientation of the modulation field orientation.* ***right:*** *Cross-tie wall in a Co film of 50 nm thickness sputter deposited on Si. The colors represent different orientations of the magnetization which are for clarity indicated by the small arrows. The lateral distribution of the magnetization orientation was measured by means of SEMPA.*

Recently we have put more emphasis on developing technologically relevant processes of nanostructure production. On the one hand we perform artificial structuring via focussed ion beam techniques, known as FIB, while on the other hand we deposit macromolecules, so called micelles, on surfaces that exhibit self-organized ordering. The ordered assembly of macromolecules is then used as a shadow mask. The latter activities are in close collaboration with the department of Physical Chemistry.

All thin film ferromagnets and nanomagnets are investigated with spatially resolving and spatially integrating techniques to obtain access to structural and magnetic properties.

Prof. Dr. Hans Peter Oepen

Focused Ion Beam (FIB)

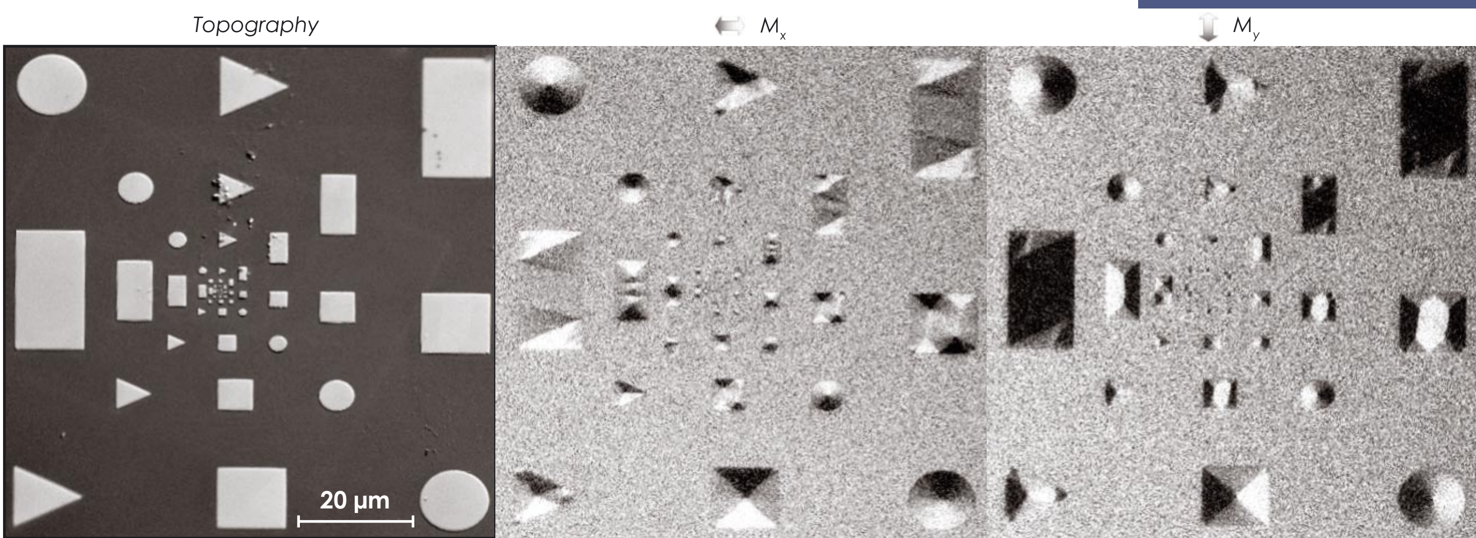
High energy ions are routinely used in surface science to remove material for cleaning surfaces. When the ion beam is highly focussed, fine structures can be written into the surface or small nanostructures can be carved out of a thin film. Such a FIB is used in our group to fabricate nanostructures from ferromagnetic films and to study the influence of shape and size on the magnetic behavior of the particle. From the technological point of view the high flexibility in structuring via FIB is most desirable as it gives access to the investigation of the influence of edges, corners and their imperfection on the magnetic behavior.

Magneto-Optic-Kerr Effect (MOKE)

One challenge with ultrathin films is the need for in-situ investigation of their magnetic properties under ultrahigh vacuum (UHV) conditions with sufficient sensitivity, i.e. in the sub-monolayer range. One of the most flexible techniques is MOKE. While conventionally the MOKE is used for measuring the so called hysteresis curves we use this technique to measure the magnetic susceptibility with extremely high sensitivity of < 30 nrad in situ.

Scanning Electron Microscopy with Polarization Analysis (SEMPA)

A conventional scanning electron microscope is used to excite secondary electrons from ferromagnetic surfaces, which are spin polarized. Detecting the secondary electron polarization gives the possibility to measure the magnetization on a large lateral scale with a resolution that is given by the focus size of the electron beam of the microscope. The advantage of SEMPA is actually its capability of measuring the magnetization orientation, which is the most valuable information when investigating magnetic microstructures. Two different microscopes are available with a resolution of 10 nm and 30 nm for structures of magnetic origin.



all 3 fig.: *Topography (left) and domain pattern (middle and right) in Permalloy microstructures obtained by SEMPA. The domain images show the magnetization distribution in two perpendicular polarization components. All three images were taken simultaneously. The Permalloy structures are 50 nm thick and deposited on oxidized Si.*

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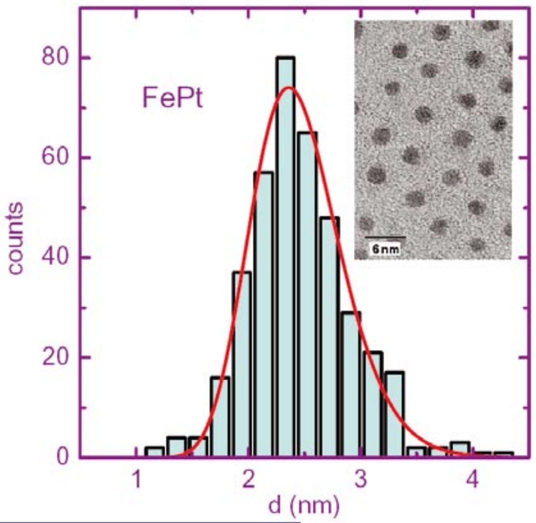
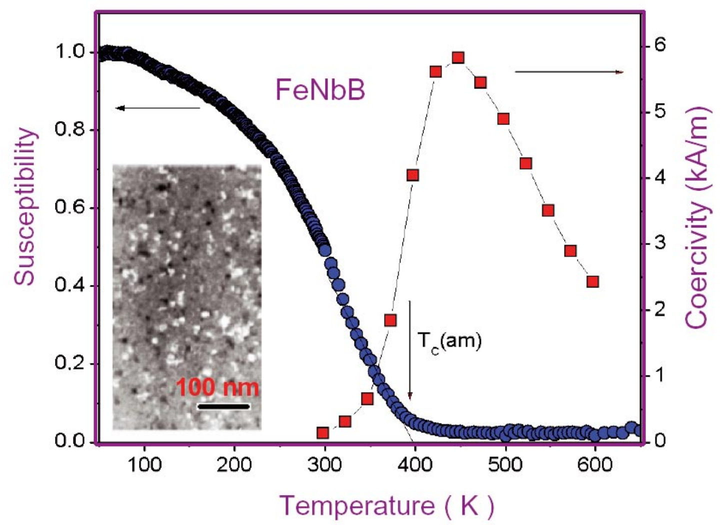
Research Activities

We investigate materials with reduced dimensions in the nanometer-scale regime. Such samples serve as building blocks with interesting features for modern magneto- and superconducting electronics. Among the samples under study are (i) ferromagnetic spheres with diameters between 2.5 nm and 9 nm imbedded in organic hosts, considered for magnetic data storage at the high-density limit; (ii) ferromagnetic crystals of sizes between 10 nm and 25 nm, grown in amorphous alloys to reveal very soft magnetic behaviour as desired, e.g. for low-loss transformers; (iii) thin ferromagnetic wires and films with magnetic nanostructures allowing for switching the resistance in very small external fields, which is of great interest for sensors, e.g. in reading heads; (iv) thin films of high-T_c superconductors from which low-loss microwave devices can be made, and (v) surfaces of superconductors, which carry supercurrents in magnetic fields much higher than the underlying bulk material.

As the main experimental technique we employ high-sensitive inductance measurements spanning an extra-ordinary wide frequency range, 1 mHz to 100 GHz, in which both dynamic magnetic and electric transport properties can be explored. These investigations are complemented by dc-magnetization and dc–conductance measurements at the low frequency end, while in the microwave regime electron spin and ferromagnetic resonance (FMR) spectrometers are available. Several of these testing grounds are equipped with superconducting quantum interference device (SQUID) detection which, for example, can trace 10^{-3} to 10^{-4} of an iron-monolayer. In most cases, the samples under study can be cooled down to 1.5 K, heated up to 800 K, and subjected to external magnetic fields up to 14 Tesla. The characterization of micro- and nanostructures is performed by polarized optical, atomic force (AFM) and magnetic (MFM) force microscopes.





left: *Histogram for diameters of ferromagnetic nanospheres imbedded in an organic matrix as shown by the TEM image of the inset. The results are described by a log-normal distribution (solid line) with small dispersion-width σ_d = 0.15 about the mean diameter 2.42 nm.* ***right:*** *The coercive field decreases rapidly below 400 K down to extremely small values, $H_c \leq 10$ A/m, which characterize the alloy as magnetically ultrasoft. This softness is directly correlated with the onset of ferromagnetic order in the amorphous phase at T_c(am), as evidenced by the increase of the magnetic susceptibility.*

Ferromagnetic Nanoparticles

As one of the favorite alloys for producing magnetic storage bits of nm-size, ferromagnetic FePt is considered due to the possibility for tuning its anisotropy field H_A by thermal treatment. Along with the particle size the magnitude of H_A has to be optimized to meet the feasibilities of thermally stable data storage and of imprinting bits. A highly diluted assembly of very small FePt-crystals has been prepared, for which the particle moments, H_A, and the stability of the particle magnetization has been examined between 10 K and 400 K.

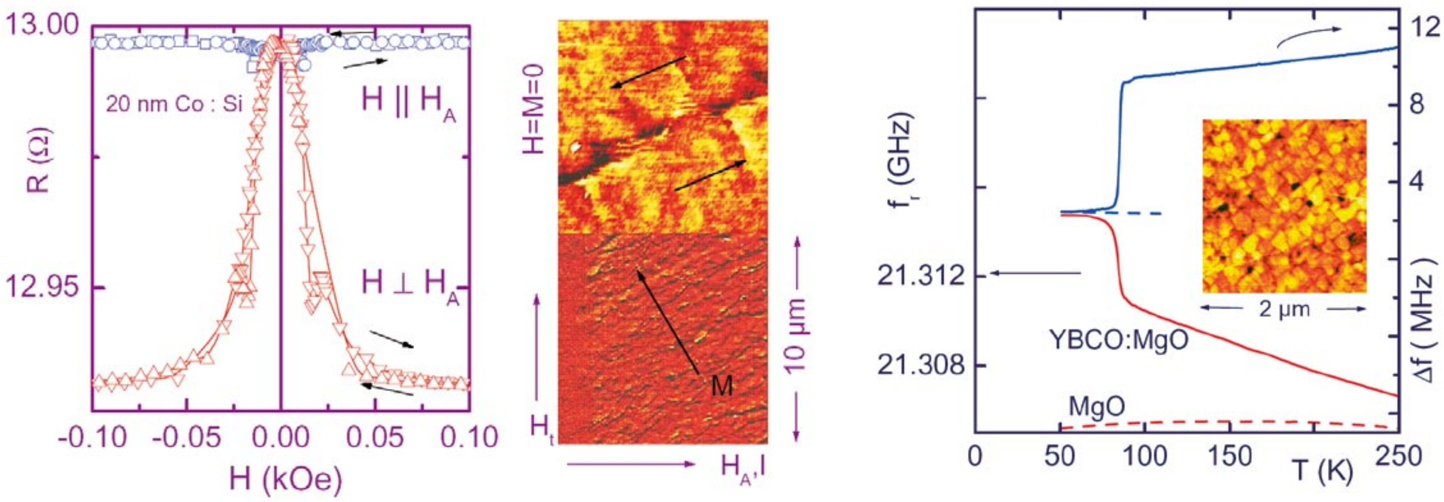
Prof. Dr. Jürgen Kötzler

Nanocrystalline Ferromagnets

In these materials, the nanocrystals are coupled by an exchange interaction provided by the host material in order to suppress the particle anisotropy H_A and to enable an easy reversal of the magnetization. For the nanocrystalline alloy $Fe_{80}Nb_7B_{13}$ (trademark NANOPERM), this softening occurs below the Curie-temperature of the amorphous matrix. The present challenge is to increase T_c(am) by strengthening the exchange via the substitution of Fe by Co (HITPERM) while keeping H_A at a low level.

Thin Ferromagntic Films: Magnetotransport

The direct and fast transformation of a magnetic signal, as emerging e.g. from a hard disc, into a voltage, constitutes one of present challenges to the design of sensors, like reading heads. The magneto-resistance of a polycrystalline Co-film that is easily deposited by magnetron sputtering has been investigated. The observed unidirectional switching of R results from (i) a rotation of a ripple type magnetization caused by a field as low as 20 Oe and (ii) the reversal of M by a longitudinal H due to the motion of Néel-walls.



left and middle: *Switching of the resistance of a 20 nm thin Co-film by a magnetic field directed transverse to the anisotropy field, H_A, in the film plane. In the longitudinal orientation, the switching is absent. This feature results from the magnetic domain structure, explored by magnetic force microscopy (MFM) shown on the r.h.s. for M=0 and H_t=25 Oe.* ***right:*** *Temperature variation of the resonance-frequency f_r and -width Δf of a microwave cavity loaded with a 50 nm thin $YBa_2Cu_3O_7$-film on a MgO substrate. The pronounced features at and below the transition of this high-temperature superconductor, T_c=86 K, are strongly influenced by an interplay between thermal vortex-antivortex fluctuations in this quasi-two-dimensional superconductor and its granular nanostructure shown by the AFM image of the inset.*

Superconductivity of thin films and surface layers

The small but finite losses of real high-T_c superconductors in electric circuits are determined by thermal fluctuations at the high operation temperatures and the nanostructural imperfections occurring in thin films (see inset to right figure). Both are of particular importance for thin films, frequently used for microwave applications.

If a magnetic field is applied parallel to the surface, superconductivity (SSC) is nucleated within a sheat being as thin as one correlation length (ξ=10-50 nm), while the bulk remains normal conducting. The interest in this well-known phenomenon has been revitalized by our discovery of a coherent state of this SSC.

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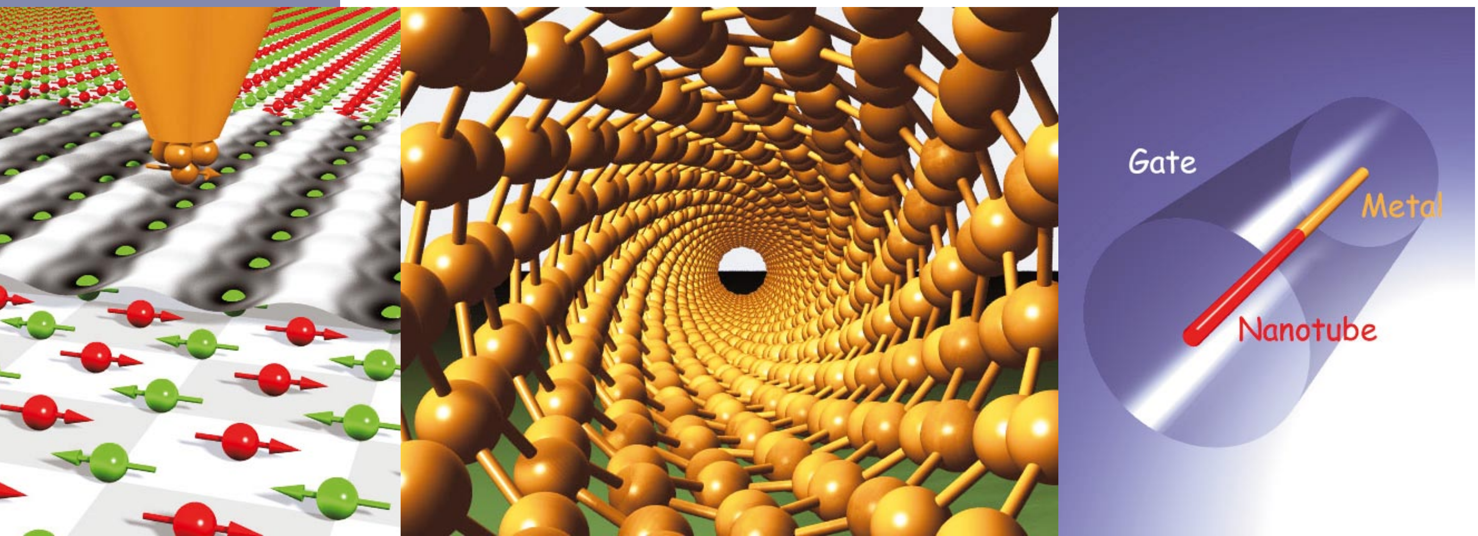
Microscopic Aspects of Spinelectronics

Junior-Prof. Dr. Stefan Heinze

Research Activities

We explore novel materials for future applications in nano- and spinelectronic devices using powerful methods of theoretical solid state physics involving computations on large computer clusters and/or supercomputers. We can calculate the properties of real nanostructures such as their electronic and magnetic structure from first-principles, i.e. free of any empirical input parameters. This enables us not only to interpret and explain unexpected experiments but to predict the properties of new materials and help to guide experimental efforts at the institute. For many technological applications the transport properties of nanostructures are crucial. However, due to their reduced dimensionality nanoscale devices such as carbon nanotube transistors behave quite differently from conventional silicon transistors. We explore the transport in nanostructures using semiclassical and quantum-mechanical models. Due to the huge number of atoms involved in real devices the electronic structure is treated with semi-empirical methods.



left: *Illustration of atomic-scale magnetic resolution with a scanning tunneling microscope (STM) using a magnetic tip.* ***middle:*** *Structure of a (7,1) (single-wall) carbon nanotube looking along the tube axis.* ***right:*** *An idealized model of a carbon nanotube transistor.*

Magnetism of Nanostructures

Low-dimensional nanostructures such as ultra-thin films, atomic chains, and single atoms on surfaces, show surprising magnetic properties, for example two-dimensional antiferromagnetism of prototypical bulk ferromagnets or complex non-collinear magnetic structures. Experimentally, scanning probe methods can be applied to elucidate their magnetic properties on a nano- or atomic scale. These tools have become indispensable for nanoscience, however, the interpretation can be difficult. We are therefore also concerned with the theory of these techniques.

Transport in Nanostructures

In the past four decades, down-scaling the size of silicon devices has led to an unprecedented enhancement of computer performance. However, further shrinking of the structures may be limited by effects such as leakage currents and increasing power consumption. In addition, quantum effects become important on the nanoscale. New materials such as nanotubes and nanowires are being intensively explored today in academic and industrial research. For example, carbon nanotubes have raised high hopes due to their unique combination of structural, electronic, and optical properties.

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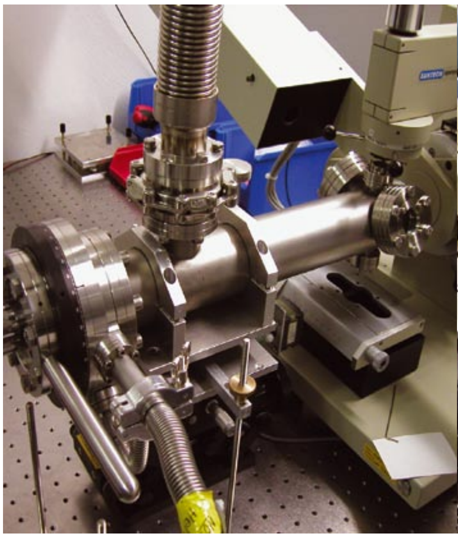
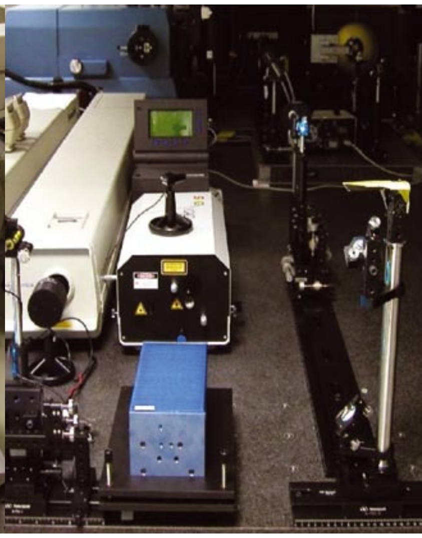
Photon Methods

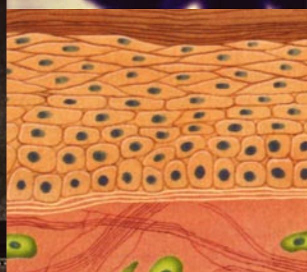
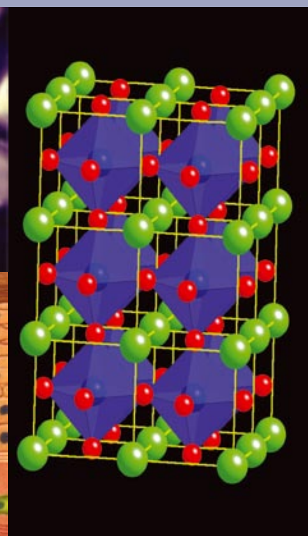
Prof. Dr. Michael Rübhausen

Research Activities

We use photon methods in the spectral range from the near infrared (NIR) to the vacuum ultraviolet (VUV) in order to study functional materials such as high-temperature superconductors, systems with colossal magnetoresistance, and bio-organic matter. Currently, we perform ellipsometric studies of the hydration dynamics in proteins and use magneto-optical ellipsometry to study spin-polarization of phase-separated systems such as cobaltates and manganites as well as of artificially patterned micro- and nanomagnets.

With Raman spectroscopy we investigate orbital ordering in manganites, short-range order in water, ordering parameters in high-temperature superconductors, and spin dynamics in magnetic systems. In particular, our results on insulating and charge-ordered manganites demonstrate the importance of excitations with broken time-reversal symmetry as well as of the Jahn-Teller coupling for the orbital ordering. Our inelastic light-scattering setup UT-3 enables Raman spectroscopy from the visible spectral range to the UV and upper VUV. The variation of the incident photon energy allows to study the detailed coupling between the electronic structure and the quasiparticle excitation spectrum. As an example, we were able to show that the gap and corresponding Cooper pair breaking peak in high temperature superconductors has a composite nature, outlining the complicated nature of superconducting order parameter.

***left 2 fig.:** The two pictures show the magneto-optical and spectroscopic ellipsometer as well as the inelastic light-scattering setup UT-3. **middle:** The top picture shows charge-ordering domains in $Bi_{0.18}Ca_{0.82}MnO_3$, the bottom one shows human skin. **right:** General perovskite unit cell for manganites and cobaltates.*

A novel VUV-Raman spectrometer, that will provide unique spectral, spatial, and temporal resolution, will be established at the VUV-FEL at HASYLAB/DESY. The first experiments will be on solids, atoms and molecules as well as biological tissues. Thus, our research group links the solid state and nanobiosciences with the present and planned light sources at HASYLAB/DESY.

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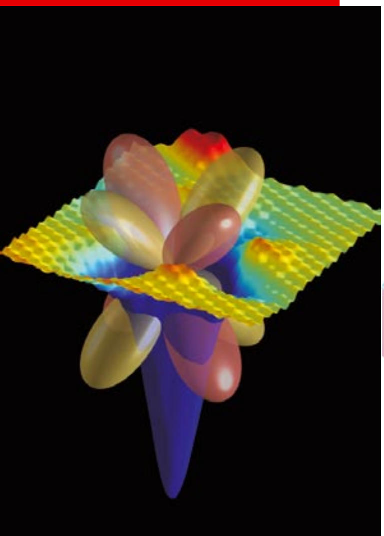
Theory of Nanomagnetism and Electronic Correlations

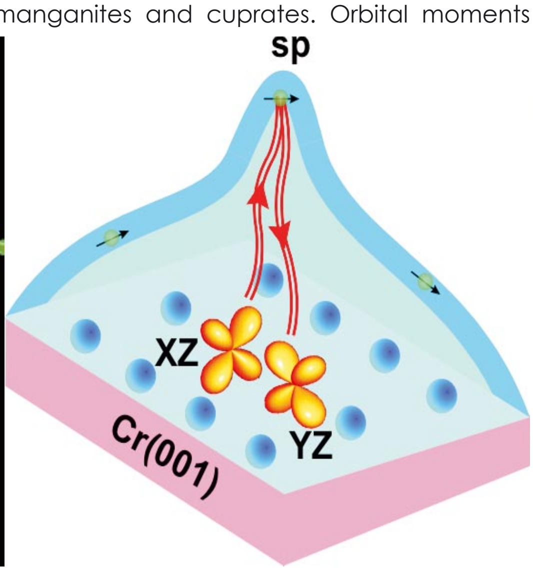
Research Activities

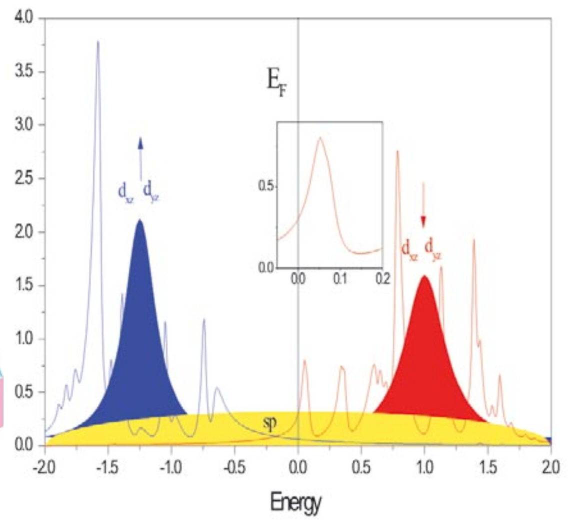
Our main research activities are related with fundamental quantum aspects of spin phenomena in nanomagnetic structures. Formation of local spin and orbital magnetic moments, effective exchange interactions as well as different spin, charge and orbital ordering depends crucially on the electronic structures of real nanosystems. We develop new theoretical approaches for an accurate description of the local quantum phenomena for correlated finite fermionic systems in a metallic environment. The necessity to go beyond the one-electron approximation has been caused by the failure of the mean-field approach to explain a complex electronic behavior of magnetic adatoms on metallic surfaces. Dynamical electron-electron correlations become very important on the nanometer scale. An efficient scheme, which unifies realistic electronic structure methods within the Local Density Approximation to the Density Functional Theory and local correlation effects within Dynamical Mean-Field Theory (LDA+DMFT), describes well the electronic structure and magnetic properties of complex materials. We design the LDA+DMFT approach on the basis of different density functional schemes: Linear Muffin-Tin Orbital (LMTO), KKR-Green functions and Projector Augmented Wave (PAW) methods. The many-body DMFT part of the problem is investigated within the Quantum Monte-Carlo (QMC) scheme, Exact Diagonalization (ED) method, or Fluctuation-Exchange approximation (FLEX).

Formation of Spin and Orbital Moments

We use the LDA+U spin-polarized electronic structure scheme to investigate the formation and ordering of the spin and orbital magnetic moments for transition metal nanoclusters and different correlated materials, including manganites and cuprates. Orbital moments and spin structures can be compared with the XMCD and SP-STM experiments for different nanosystems. Correct orbital polarization in the LDA+U approach allowed us to study effects of reduced dimensionality on the spin and orbital magnetism.







left: *Real-space STM image of Cr(001) surface and the orbital-Kondo model.* ***middle:*** *Orbital fluctuation due to interaction with conduction electrons.*

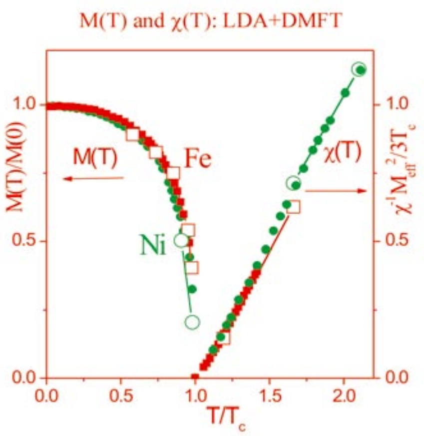
right: *Formation of the Kondo resonance in an orbitally degenerate lattice model.*

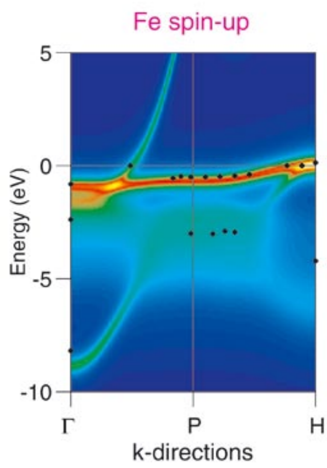
Exchange Interactions

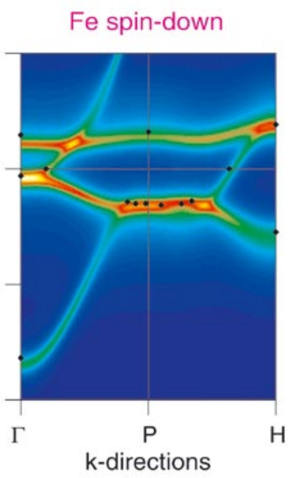
We developed an efficient scheme for the first-principle calculations of exchange interaction parameters in spin systems based on a so-called "magnetic force theorem" in the density functional theory. Existing analysis of the exchange integrals for different classes of magnetic materials such as dilute magnetic semiconductors, molecular magnets, colossal magnetoresistance perovskites, transition metal alloys, and hard magnetic materials shows the strength of this approach. We generalized the magnetic force method for correlated systems to study the exchange interactions in transition metal clusters. The anisotropic exchange interactions in Rare-Earth systems, including oxides and chalcogenides, can be investigated. We can calculate the effective exchange interactions for new magnetic systems as a function of structure, composition and charge doping.

Finite Temperature Magnetism

We use the LDA+DMFT scheme to develop a quantitative theory of finite-temperature magnetism of the iron-group transition metals. The magnetic properties of Fe, Co, and Ni and their alloys can be described properly if we take into account correlation effects in the partially filled d-shell and competition between localization from the Coulomb interactions and delocalization from the band structure effects in itinerant electron systems. We use the ab-initio dynamical mean-field theory to investigate the spectral function and the finite-temperature magnetic properties of new transition metal systems.







left: *Temperature dependent magnetic moment and high-temperature susceptibility for itinerant magnets Fe and Ni in the LDA+DMFT scheme in comparison with experimental data.*

middle: *Calculated spectral function for Fe (spin-up electrons).* ***right:*** *Spectral function for Fe (spin-down electrons). Points represent the experimental maximum in spectral function.*

Correlation Effects in Nanosystems

We develop a numerically exact Continuous Time Quantum Monte-Carlo (CT-QMC) scheme to describe correlation effects for finite fermionic systems in a metallic bath. This approach is appropriate for numerical investigation of fermionic path integrals with the general action included time-dependent multi-orbital electron-electron interactions for different clusters and hybridisation with the environment. We apply the CT-QMC approach to investigate the local correlation effects for magnetic nanoparticles on metallic surfaces. A suppression of the Kondo resonance by interatomic exchange interactions for different cluster geometry can be investigated. For practical design of new nanodevices it is important to understand the mechanism of magnetic or Kondo behavior of complex transition metal systems.

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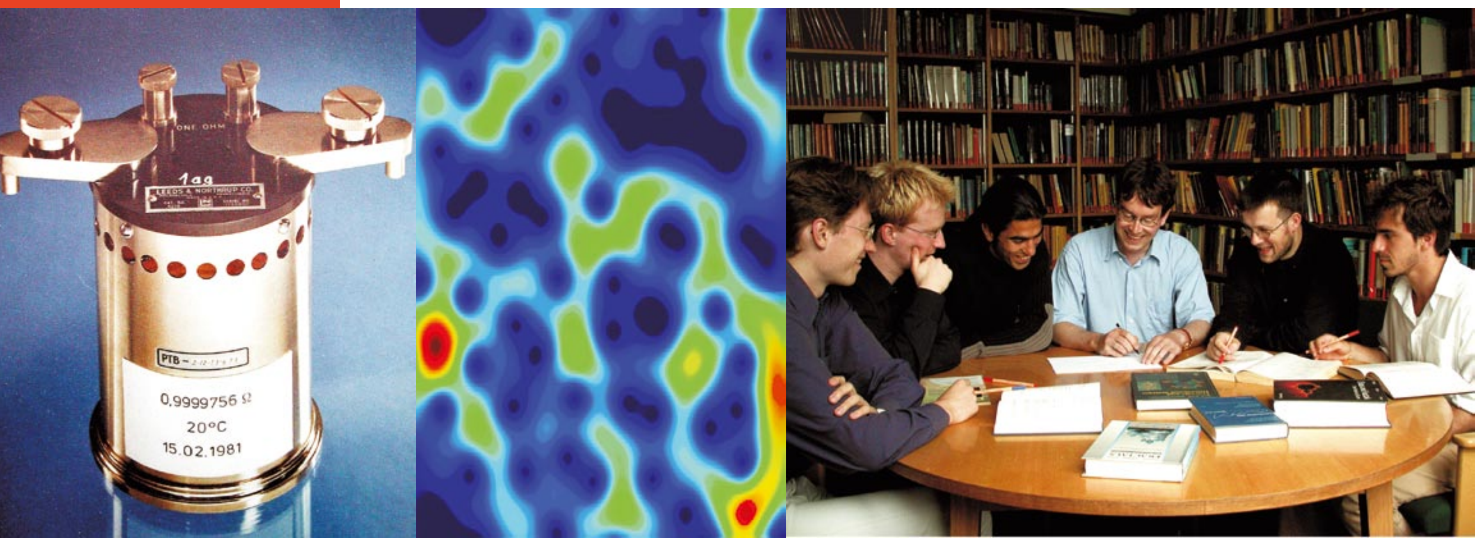
Mesoscopic Quantum Physics

Research Activities

The research on systems on the nanometer scale naturally must consider the influences of quantum mechanical properties of matter, especially at low temperature. In the „Mesoscopics Group“ such effects are studied by using theoretical methods. These include techniques ranging from analytical theory to computational methods. Among the phenomena under investigation are disorder induced localization of wave functions being closely related to quantum interference and giving rise to a metal-insulator quantum phase transition. The electron transport in the quantum regime is not only influenced by impurity scattering but is dominated by geometrical and magnetic confinement. This causes quantization of conductance. In addition, electronic non-Fermi liquid correlations are of outstanding importance. Also the electron spin causes distinct quantum dynamics, last but not least due to the relativistic spin-orbit interaction.

Quantum Interference and Quantum Phase Transitions

In order to study quantum interference and localization we use analytical techniques based on diagrammatic perturbation theory and supersymmetric field theoretical approaches. In order to quantitatively investigate specific models we use advanced numerical scaling techniques that have been developed within our team. We identified the universal critical features of the metal-insulator transition induced by disorder. Also we have established the Integer Quantum Hall Effect as a quantum phase transition. This is important for the application of the effect in metrology.



__left:__ 1 Ohm, a standard resistance as it was used before the Quantum Hall Effect has been introduced in 1992 as an international standard of the "Ohm". __middle:__ A "Swiss Cheese" quantum wave function in a two dimensional random potential landscape, introduced for understanding the Quantum Hall Effect as a quantum phase transition. __right:__ Communicative atmosphere in a discussion between researchers in the library of the Center for Solid Sate and Nanostructure Physics.

Quantization of Conductance and Correlations

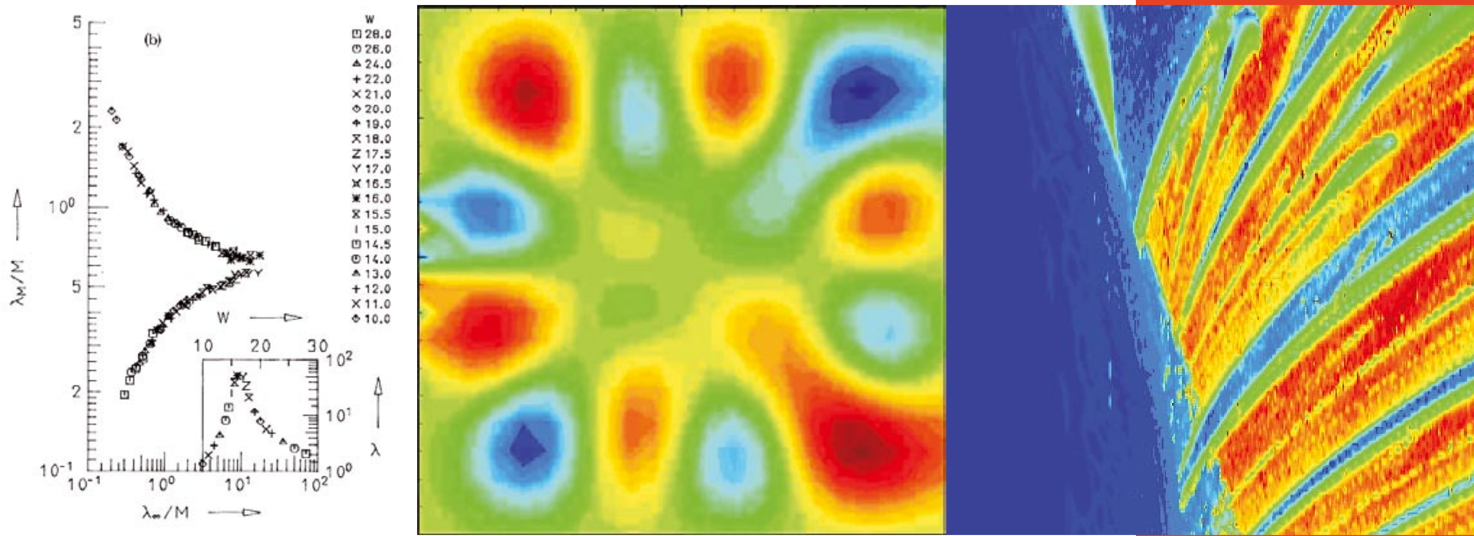
Quantum mechanical selection rules can give rise to quantization effects in the electrical conductance. Examples are the Coulomb blockade and the spin blockade in quantum dots and quantum wires due to the quantization of charge and spin. In quantum wires, the electronic interaction leads to distinct non-Fermi liquid effects. "Luttinger liquid behavior" has recently been investigated experimentally in detail in semiconductor systems and carbon nanotubes. The nonlinear transport properties of impurities embedded in a Luttinger liquid

Prof. Dr. Bernhard Kramer

lead also to distinct electromagnetic radiation effects. Quantum interference is destroyed by the coupling between the electrons and bosonic excitations such as phonons. With respect to applications of quantum dots for implementing qubits, the investigation of the conditions for quantum coherence is important. We have found that in nanostructures under certain conditions the coupling to a phonon bath may be completely quenched.

Quantum Spin Dynamics in Nanostructures

Besides classical magnetic effects the electron spin can cause characteristic quantum dynamics in nanostructures. This can lead to anomalous quantization of magneto-conductance. Most strikingly, scattering of electrons at impurities and at inhomogeneities in the presence of spin orbit interaction may lead to spatial spin patterns that reflect the spin polarization of the quantum mechanical wave functions in a device.



left: *Universal one-parameter scaling of the correlation lengths at the disorder induced metal-insulator transition. Original numerical data from 1981. In the mean time the accuracy of numerical calculations have been improved by two orders of magnitude and universality has been established quantitatively.* ***middle:*** *Spin polarization of a non-equlibrium state in a rectangular quantum billiard in the presence of spin-orbit interaction. Blue and red denote opposite polarizations.* ***right:*** *Regions of stability of the driven mathematical pendulum. Blue denotes stable, red unstable regions in the plane of driving amplitude and frequency.*

Students' Research Projects

An example of an advanced student project that can lead to the forefront of the research is the detailed study of the driven mathematical pendulum which can be considered as the quantum analogue of an electron in a quantum ring subject to a homogeneous electric field in the presence of a time dependent driving field. Coupling to a bath is modelled by a random time dependent external force. Such a system shows extremely rich behavior which includes classical and quantum chaos and in principle is accessible for experiments on nanoscale systems.

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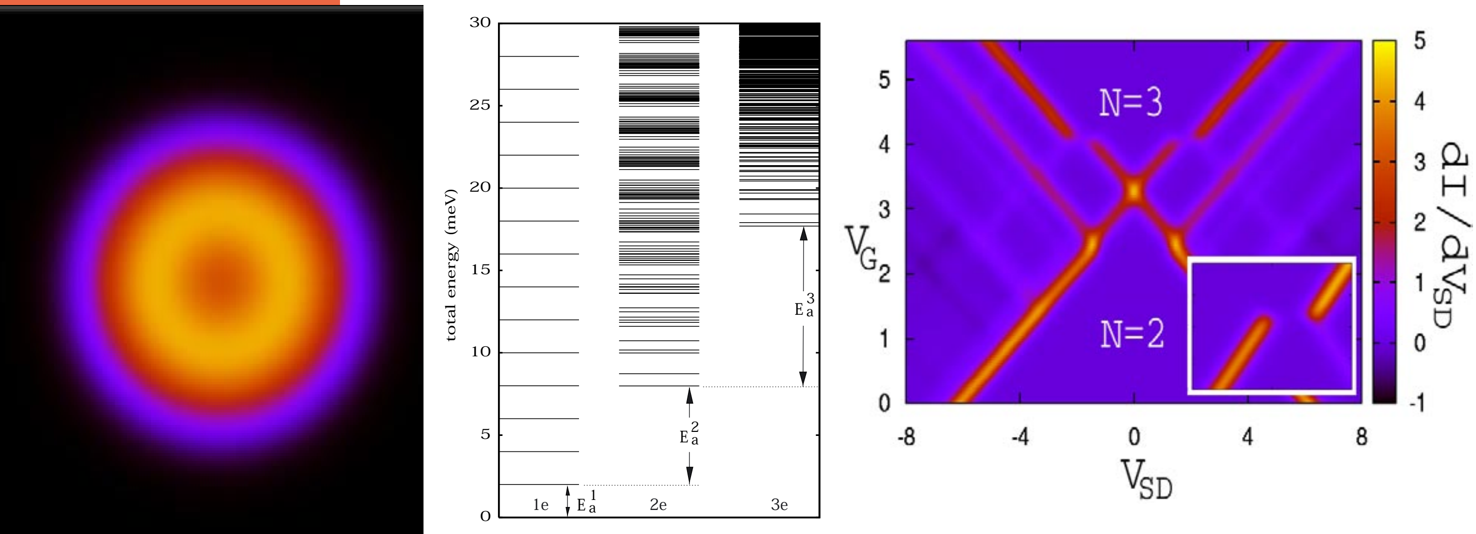
Research Activities

Correlated - also called *entangled* - states are a unique manifestation of quantum physics. In a correlated many-body state particles cannot be considered as entities on their own but each particle is inseparately entangled with any other particle. Thus, manipulation of one particle inescapably influences all other particles. Among electrons this complex interplay has strong implications for the electronic properties of low-dimensional systems. Their investigation is the central topic of research in our group.

In condensed matter the cause for correlations between the electrons is their mutual Coulomb interaction. Although it might seem paradox, interactions are the more important the lower the electronic density. Therefore, low-dimensional electron systems are paradigm for studying correlation effects. Due to immense achievements in their technology semiconductor structures serve as perfect realizations of strongly interacting electron systems. Structures of different dimensionality and topology can be fabricated and correlation effects are observed in a variety of systems reaching from zero-dimensional quantum dots and one-dimensional wires and rings to two-dimensional quantum wells.



left: *Integrated density of a 5-electron nanocrystal as it would be measured in an STM experiment.* ***middle:*** *Spectra of a two-dimensional quantum dot occupied by one (left), two (middle) and three (right) electrons.* ***right:*** *Charging diagram of a nanocrystal at the transition between two and three electrons. The ground state transition is partially suppressed.*

Quantum dots

In many aspects semiconductor quantum dots at the submicron scale resemble atoms: They host a fixed number of electrons which populate discrete energy levels. Quantum dots can be assembled to form larger units such as artificial molecules and lattices. Due to their simplicity quantum dots are ideal objects to study the influence of electronic correlations on optical as well as on transport properties. This applies equally well to theoretical as experimental approaches and it is a special treat of these systems that our calculated results can most often be verified experimentally. In single as well as in double quantum dots we could demonstrate strong suppression of transport due to correlation induced selection rules. Since interacting electron systems of finite size can be treated analytically only in very rare cases, we approach quantum dots numerically. Software packages have been developed to cope with quantum dot systems of various shape and size as well as with different electron number. At the same time, the development of refined methods, especially in the field of transport calculations, require considerable analytical work. Applying diagrammatic techniques we have been able to extend transport calculations for interacting quantum dot systems to include all cotunneling processes.

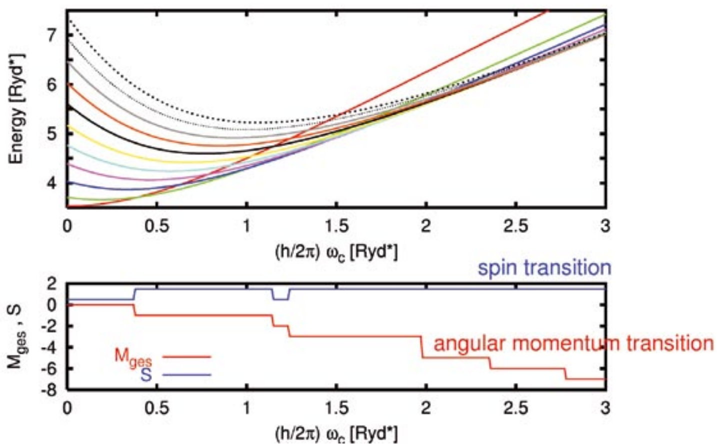
Prof. Dr. Daniela Pfannkuche

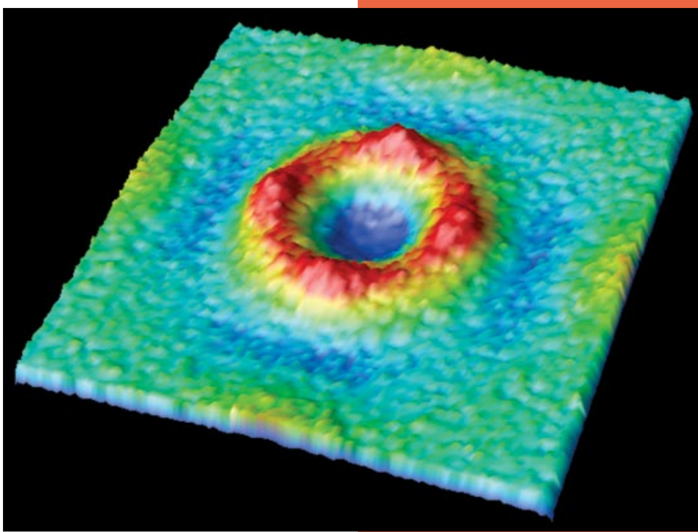
2D - Systems

For two-dimensional systems correlation effects are most pronounced when the electrons are subjected to a strong magnetic field. This regime of the *fractional quantum Hall effect* has attracted considerable interest over the years. While the theoretical treatment of strongly interacting particles most often is an extremely challenging task, theory succeeded in casting the electrons of the fractional quantum Hall regime into a zoo of different weakly interacting quasi-particles. Thus, a lot of experiments can be explained in an astoundingly simple manner. The most prominent of these quasi-particles is the *composite fermion*, a compound of an ordinary electron dressed with two flux quanta. This flux attachment mimics the repulsion between the electrons. In most cases the connection between the quasi-particles and their original, the interacting electrons, is not well known. Our aim is therefore, to disclose the quasi-particles within an electronic description of the system and to investigate their properties. A recent example for this are our investigations of quasi-holes passing through a point contact.

Spin - Systems

Most obviously, dealing with interacting electrons includes dealing with their spin. The Coulomb interaction in these systems most naturally leads to spin-spin interaction and thus to magnetic phenomena. In semiconductors such as GaAs the electronic spin is extremely stable due to its weak coupling to the environment. This renders it suitable for external manipulation. Whether in quantum dots as realization of a qubit or as carrier of information in spintronic devices the utilization of the electronic spin is one of the major challenges in the future. We contribute to this extremely interesting field of research with a variety of investigations such as spin stability in quantum dots, spin transport in one-dimensional wires and spin structures in inhomogeneous quantum Hall systems.





left: *Spectrum, spin and angular momentum of a double quantum dot occupied by three electrons as a function of an applied magnetic field.* ***right:*** *Composite fermion: The electron at the center of the figure is accompanied by two vortices. One of them is located at the position of the electron, the other one is located within the ringlike probability distribution at a certain distance from the electron.*

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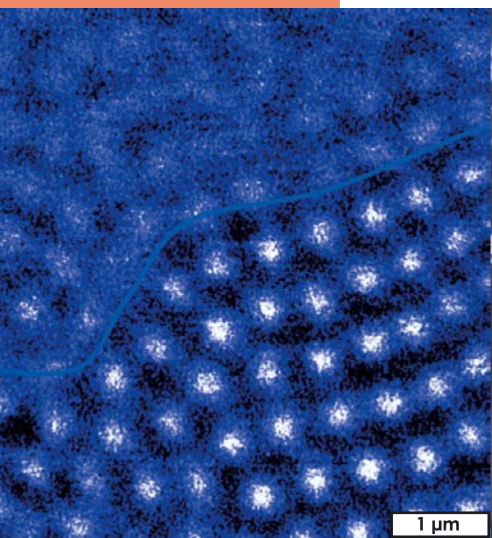
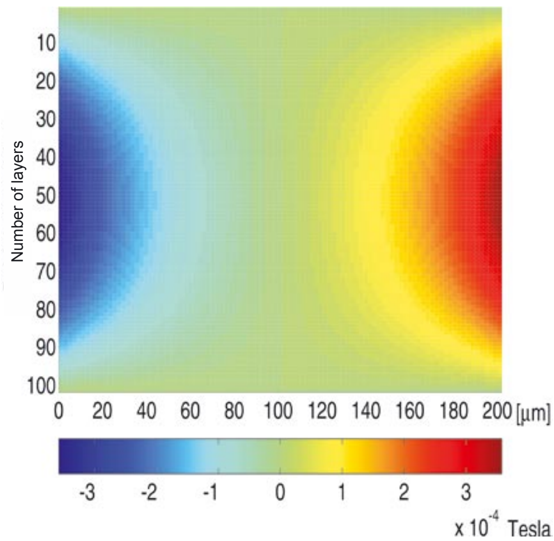
Theory of Superconductivity

Superconductivity is an intriguing phenomenon with great potential for applications. The lossless conduction of d.c. currents below a certain transition temperature T_c could provide great energy savings in the transmission of electrical power. It also allows maintaining large magnetic fields without energy consumption which is important to the power generating and the mining industries, as well as for magnetic resonance imaging (MRI), Below T_c a temperature dependent fraction of the charge carriers condense into a macroscopic quantum mechanical wave function. This condensate is responsible for lossless conduction. A.C. currents experience a finite resistance at all temperatures below T_c. The reason is the tiny but nonetheless finite mass of the charge carriers, which prevents the condensate from shorting out the applied a.c. voltage. As a result, uncondensed charge carriers, which are present at all temperatures albeit in decreasing number, cause Joule losses much as in the normal state. However, sufficiently below T_c, the real part of the conductivity σ_1 is usually very small. There are exceptions, but since the imaginary part σ_2 increases rapidly below T_c for frequencies well into the GHz regime, the penetration depth and hence the volume, in which Joule losses can occur, is greatly reduced. Superconducting resonating structures have, therefore, much higher quality factors than the same structures made of copper. Such superconducting structures are used in high energy physics in the form of cavities to accelerate particles, as filters in base-stations of mobile phone networks, or as antennas in MRI machines to improve spatial resolution. An important theoretical realization was that the purest materials do not give the highest quality factors. A delicate balance has to be struck between the penetration depth and the dissipation per unit volume.

Quite a different set of applications follows from the ability of supercurrents to pass through thin insulating barriers (Josephson junctions). Magnetic flux in a superconducting ring containing a Josephson junction takes on only certain quantized values. This permits the detection of tiny magnetic fields with so called Superconducting Quantum Interference Devices (SQUIDS). This is very useful in many fields of research as well as for non-invasive medical diagnostics.





left: *Abrikosov vortex lattice of $Bi_2Sr_2CaCu_2O_8$ with a phase boundary between a solid and a liquid vortex state observed by low-temperature magnetic force microscopy.* ***middle:*** *Superconducting cavity for accelerating particles in high energy physics experiments at DESY.* ***right:*** *Magnetic field distribution in a stack of 100 coupled superconducting layers which conducts a current of 1500 A / cm².*

Superconductivity is by no means a rare phenomenon: Almost all conductors become superconducting at some T_c except for the best conductors like Cu, Ag, Au and

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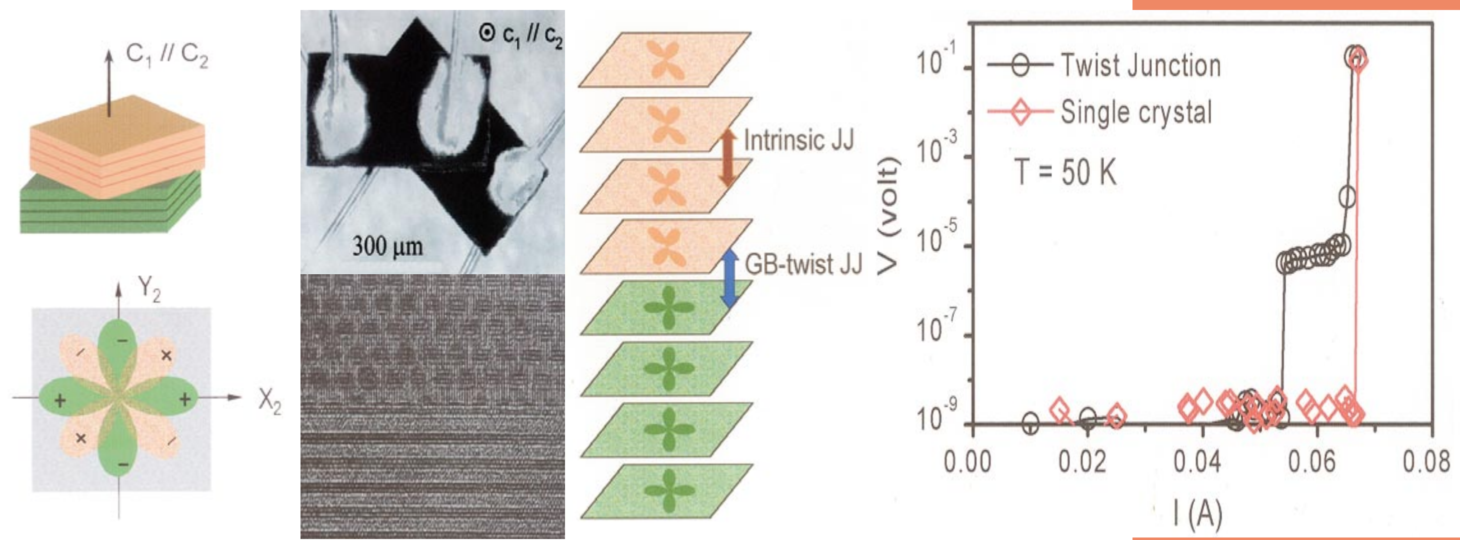
ferromagnetic metals like Fe, Co, Ni. Which properties control T_c is an important question. It is also the most difficult to answer theoretically. For some classes of materials this question seems to be settled. However, for the high temperature superconductors with T_c's as high as 150 K (-123°C) the mechanism responsible for superconductivity has not been firmly established. Small changes in the chemical composition turn these superconductors into antiferromagnetic insulators. This close proximity to a magnetically ordered state is certainly relevant for the superconducting state. Its precise nature is far from clear, though, but one can hope that detailed theoretical analysis undertaken in this group of experiments performed at the Brookhaven National Laboratory can help to shed some light on this problem, as well as experiments, in which the Josephson current through c-axis twist grain boundaries is measured as function of twist angle.

Apart from questions related to the symmetry



left: *Schematic representation of a c-axis twist junction of a layered compound and a visualization of the symmetry of a d-wave order parameter above and below the twist grain boundary.* ***middle:*** *Top view photomicrograph of a 45° c-axis twist junction, showing three of the six contacts. TEM image of a 37° c-axis twist grain boundary between single crystals of tetragonal $Bi_2Sr_2CaCu_2O_{8+\delta}$. The top crystal, showing some superstructure, is viewed along the a-axis. The distance between conducting CuO_2-plains is so large, that these planes form intrinsic Josephson junctions.* ***right:*** *Critical current of a 50° twist junction versus intrinsic junctions. The critical current through the twist junction is smaller because of the smaller area. The critical current density does not vary with twist angle.*

of the superconducting state, the maximum magnetic field up to which superconductivity can exist is investigated as are transport properties like the complex a.c. conductivity and the thermal conductivity. Single particle properties which can be measured by scanning tunneling spectroscopy (STS) and angle resolved photoemission spectroscopy (ARPES) are also studied. The theory takes into account intrinsic material properties like the strongly anisotropic crystal structure, the tight binding nature of the band structure and the strong correlations between charge carriers. Disorder effects are taken into account because they are essential to understand microwave losses at low temperatures, but they can also provide information on the nature of the superconducting state.

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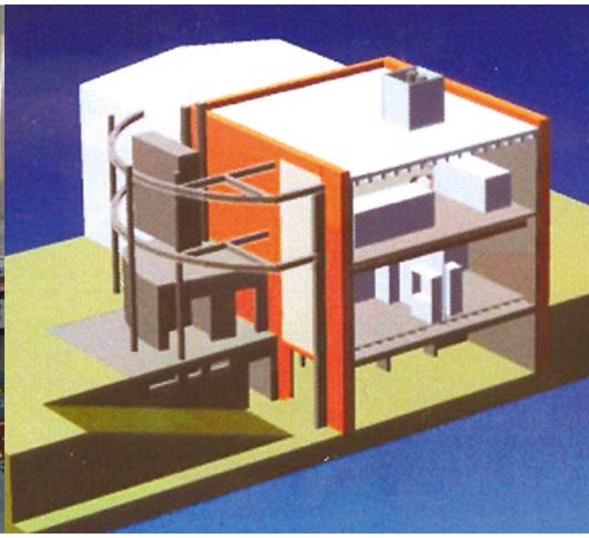
Cleanroom

A cleanroom of class 100/1000 with an effective area of about 100 m^2 supplies optimum conditions for processing semiconductors and other materials with state-of-the-art technologies. In addition to standard equipment provided for photolithography, four more specific areas are set up for the definition and realization of quantum structures in the nanometer regime.

Interference lithography operated with an Argon ion laser at visible and UV wavelengths allows the preparation of periodic nanostructures on macroscopic areas of semiconductors, metals and insulators. This enables quantum effects to be studied by far-infrared Fourier and laser-spectroscopy, Raman scattering or photoluminescence in arrays of, e.g., quantum wires, quantum dots and small ferromagnets.

The scanning electron microscope is equipped with a system for electron beam writing to define discrete nanostructures like single quantum dots for the study of few-

left: *The molecular beam epitaxy system.* ***middle:*** *Sketch of the cleanroom with it's three floors for air-conditioning (upper), lab area (middle) and air-exhaustion (lower).* ***right:*** *Scanning electron microscope (upper) and different systems for growth of thin film structures (lower)*

electron systems on semiconductors and hybrid semiconductor-superconductor or semiconductor-ferromagnet structures for the investigation of proximity superconductivity in degenerate electron gases in semiconductors and spintronic devices.

A third area is devoted to the growth of thin films, i.e., PECVD of silicon dioxide near room temperature, magnetron sputtering of niobium and thermal evaporation of various metals.

An important segment accommodates equipment for reactive ion etching and deposition of semiconductors and metals. Two reactive ion etching systems are available for the etching of AlGaAs/GaAs and Si/SiO_2 semiconductors. A plasma system allows deposition of Si nitrides and Si oxides. All systems are optimized for a low damage preparation of small semiconductor quantum structures.

The cleanroom is supplemented by a preparation room of class 10 000 with an area of about 80 m^2 that houses the molecular beam epitaxy (MBE) facility. It consists of an UHV-system in which a growth chamber equipped for III-V semiconductor heterostructures and a processing chamber are integrated. Presently the system is extended with a second growth chamber for highest purity crystal growth and an UHV-scanning-tunneling microscope.

In 2004 a new building was finished which has about 200 m^2 of higly specialized lab space for experiments in the field of spintronics. This new building houses a dedicated electron beam writing facility as well as a second MBE system.

Facilities

Laboratories with vibration-decoupled foundations

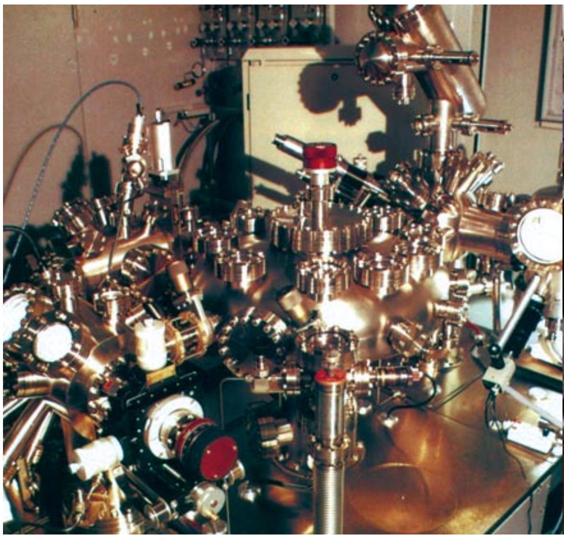
Special vibration-decoupled and acoustically shielded laboratories are available for atomic-scale microscopy, spectroscopy, and manipulation of materials based on scanning probe methods. This allows to perform sophisticated experiments, such as spin-polarized scanning tunnelling spectroscopy, inelastic scanning tunnelling spectroscopy, and three-dimensional force-field spectroscopy which require a vibration- and noise-free environment over extended time periods of up to several days. In addition, manipulation of individual atoms and molecules can be performed over long periods of time allowing the bottom-up construction of complex nanostructures.

PHYSnet Computer Center

IT-support for the whole Center of Solid State and Nanostructure Physics is provided by the PHYSnet Computer Center. This Computer Service facility is the biggest independent computer center of Hamburg University. It offers all services of a modern competence center and all network services of a modern IT-service center. It supports more than 980 computers using several failure tolerant server clusters and three high performance parallel-cluster-systems. Central file server systems with 6 TByte SAN-storage capacity export dataspace via network into all standard operating systems. PHYSnet Computer Center manages a modern computer network with Gigabit backbone spread over several parts of Hamburg and is responsible for all IT-security affairs.

Fine Mechanical and Electronic Workshops

Oftentimes the extraordinary high mechanical and electronic requirements of novel experiments can not be realized by commercial standard components. Here the workshops offer professional support in the implementation of new ideas into concrete experimental devices. Due to the long lasting close teamwork with the scientists of the Center, the technicians and engineers have gathered an extensive specialist knowledge,



left: An *Ultrahigh Vacuum* chamber housing a scanning tunneling microscope and several other devices for sample preparation and analysis. ***middle:*** *Massive foundations, separated from the building, are necessary to decouple vibrations from the highly sensitive experiments.* ***right:*** *The fine mechanical and the electronic workshop support the design and implementation of new devices and experiments.*

which is continuously imparted in the frame of apprenticeship. The fine mechanical workshop possesses substantial know-how about the machining of a variety of materials, e.g. ceramics, tungsten, titanium, molybdenum, oxygen free copper. The electronic workshop develops and makes tailored, optimized circuits for the specific purposes.

How to reach us ?

Railway

Get off at *Dammtor* station. From *Dammtor* it is a 10 minutes walk to the Center.

Plane

From the airport take the Bus 110 to *Ohlsdorf* station, then the subway U1 to *Stephansplatz*. From *Stephansplatz* it is a 10 minute walk to the Center. The overall travel time is about 45 minutes.
The charge for a taxi from the airport to the Center is about 30 €.

Car

Follow the signs to *Messe* and *CCH*.
A few parking lots are available in the *Jungiusstrasse*, *Bei den Kirchhöfen* and *St. Petersburger Strasse.* More parking lots are available in the basement garage of the CCH.

Regional Public Transport

The following stations are all within a 10 minutes walk to the Center:

Railway: S11 / S21 / S31 to *Dammtor*

Subway: U1 to *Stephansplatz*, U2 to *Gänsemarkt* or *Messehallen*

Bus: 3 to *Sievekingplatz*, 4 / 5 / 109 / 112 to *Stephansplatz*

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GIF	German-Israeli Foundation
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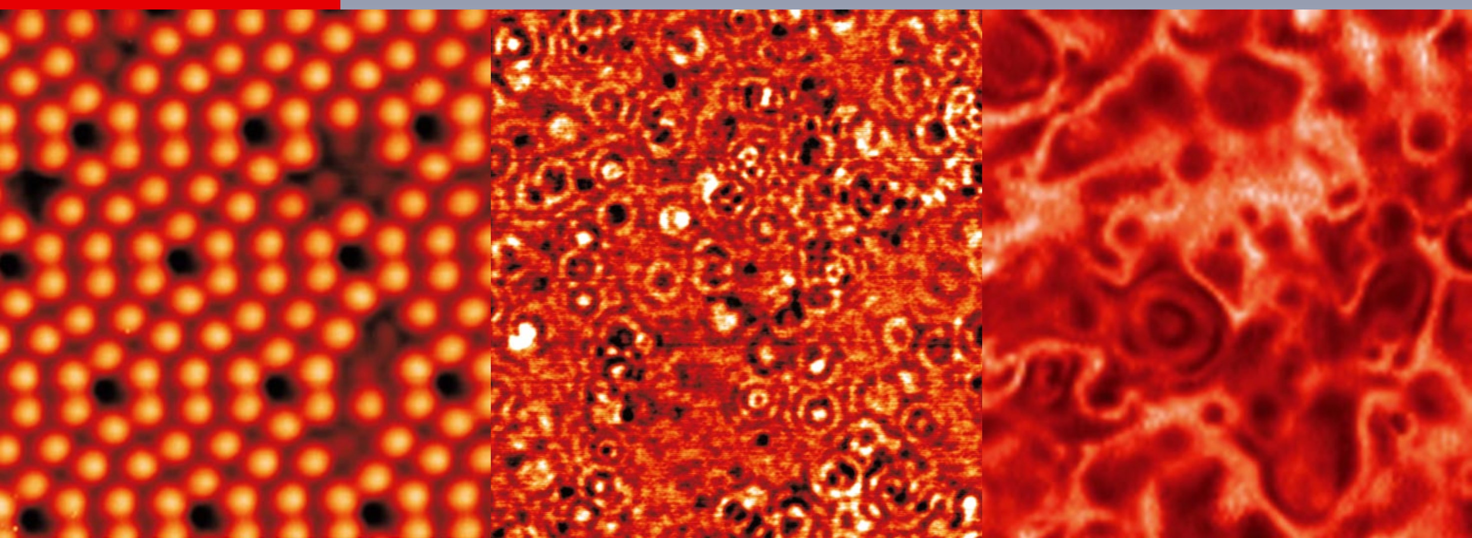

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