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Flashback to 2014

2014 was a crucial year for the Leibniz Institute for Solid State and Materials Research Dresden (IFW): We underwent a serious evaluation procedure, had a change in the scientific management at the same time, started a new research program with a complete new structure and paved the way for a new director of one of the five IFW institutes.

The most important event was the evaluation of the Institute by the Senate of the Leibniz Association. All Leibniz Institutes are institutionally funded by the federal government and by the German Länder in equal shares. The justification of this funding has to be affirmed for each institute in intervals of seven years by an evaluation panel set up by the senate commission of the Leibniz Association. The prerequisite of confirmed funding is high quality scientific work and its high relevance for the whole society. A panel of renowned, international scientists visited the institute for two days in July 2014. The whole institute prepared very carefully for this third evaluation since the foundation of IFW. We look quite optimistically forward to the final report that will be published by the Leibniz Association Senate in spring 2015.

Immediately before the evaluation visit Prof. Dr. Manfred Hennecke has been appointed as temporary Scientific Director of IFW. Having been the President of Federal Institute for Materials Research and Testing (BAM) for 11 years he retired in 2013. He returned from retirement to fill the position of the Scientific Director of IFW which was vacant due to the request of Prof. Dr. Jürgen Eckert to be released from this office and to revert to his role as the director of one of the five IFW institutes. One of the main task of Professor Hennecke is to push changes in the management structure of IFW in a way that enables for long-term stability.

Further personnel changes in the Institute’s management concern the directorship of one of the five IFW’s institutes: the Institute for Metallic Materials which was headed by Prof. Dr. Ludwig Schultz up to the end of September 2014. The successor in this position is about to being appointed which will have new impact on the research program of the whole IFW.
Scientifically, 2014 was a very productive year for IFW. The appendix gives a complete record of the publications, invited talks, patent applications, completed graduations and theses, academic events, and guest stays. In the main part of this Annual Report outstanding scientific results are presented according to the new structure of the IFW’s research program which is organized into four large research areas.

- Research Area 1: Functional quantum materials
- Research Area 2: Function through size
- Research Area 3: Quantum effects at the nanoscale
- Research Area 4: Towards products

A new aspect of this program is that it consists of Research Topics that are interdisciplinary and bring closely together researchers from different IFW institutes. The creation of such additional synergy, which strengthens the collaboration within the IFW, is one of the main goals of this new program. In addition, the new project-oriented research structure allows for a considerable amount of flexibility in particular for the subtopics and will provide a dynamical framework for developing, nurturing and consolidating our future research lines. While being distinctly multidisciplinary, there is a clear common aspect to all activities of the IFW Dresden: all researchers at the IFW Dresden investigate yet unexplored properties of novel materials with the aim to establish new functionalities and applications. The range of materials that are investigated in this context is broad but well-defined. It contains Quantum Materials, a highly topical class of materials in condensed matter physics as well as Functional Materials, representing an important part of modern materials engineering. In the last years Nanoscale Materials, which are a strong focus of present day materials science and a crucial material class for cutting-edge developments in electrical engineering, came in the fore of our research in several IFW institutes. These three classes, Quantum Materials, Functional Materials and Nanoscale Materials, provide the three materials-oriented pillars of the IFW. Each of these three new research areas, connecting two different classes of materials, follows the motto of the Leibniz Association “theoria cum praxi”: They consist of well-defined research topics connecting basic science with applied research and bring together researchers from all five IFW institutes. The research area “Towards products” binds together materials science and engineering that is at the borderline to prototypes or products. Establishing, fostering and promoting the contact to industry partners is the main aspect within this activity.
Flashback to 2014

As a Leibniz Institute the IFW is budgeted by the federal government and the German federal states in equal parts. However, a considerable extension of capability is the amount of third party project funding which is also an important index of quality. The level of third party funding in 2014 amounts to 11.874 Mio. Euro – a level at the forefront of the Leibniz Association. Most of this project funding was acquired in a highly competitive mode from the DFG and the EU. In particular the grant of the new Collaborative Research Centre 1143 on “Correlated magnetism: From frustration to topology” where the IFW is collaborating with the TU Dresden shows the competitive capability of the IFW. Among the large number of third party funded projects are three DFG-Priority Programs that are coordinated by the IFW, further eight DFG-Priority Programs where the IFW participates, as well as three DFG Research Groups where the IFW participates. As in the previous years the IFW has been very successful in initiating EU projects and participating in them. Though quite time consuming these project applications have very positive effects on networking the IFW with other European groups. 9 of our 16 EU projects running in 2014 have been coordinated by the IFW.

Essentially publicly funded, the IFW is obliged to make its research results public. About 380 publications in scientific journals and conference proceedings report on the IFW’s research results on the year 2014. In almost 200 invited talks the Institute’s scientists presented their work at other places around the world. 19 patents were issued for the IFW, and applications for 16 more patents have been made. Apart from these scientific communications the IFW continued its large efforts to make scientific work accessible for the general public and to inspire young people to study science or engineering. The IFW took part in many joint actions like the lecture series “Physics on Saturday”, “Junior Doctor” or the Summer University of the TU Dresden. Besides these big events we organize almost weekly lab-tours for various visitor groups, from school classes through official representatives to guests from foreign organizations. Especially the IFW’s superconducting test facility SpuraTrans in Dresden-Niedersedlitz has proved very popular among visitors, be it representatives from companies, students groups or politicians.

With respect to the infrastructural development we have put large efforts during the last years into the realization of a new annex building with special laboratory areas and additional office space. In beginning of 2014 construction works were completed and we celebrated the inauguration of the annex building. Right in between the old and the new parts of the building a nice atrium was created which already have proved very useful for various events.
2014 was again a yielding year with respect to prizes and honors awarded to members of the IFW. Among them are the International Dresden Barkhausen Award for Prof. Dr. Oliver G. Schmidt and the DGM Prize for Prof. Dr. Jürgen Eckert. Dr.-Ing. Alexander Kauffmann was awarded two prizes for his outstanding PhD thesis: the DGM Junior Award and the Prize of the German Copper Institute. The most prominent prize for an IFW member surely was the German Federal Cross of Merit (first class) for Prof. Dr. Manfred Hennecke, although it was not related to his activities at our Institute. A full list of prizes awarded to members of the IFW is included in the appendix.

Furthermore, three scientists of the IFW have been offered a chair at universities in 2014: Dr. Maria Daghofer accepted a call to the University of Stuttgart and Prof. Dr. Jürgen Eckert is negotiating with University Leoben (Austria) and Dr. Jochen Geck with the University of Salzburg (Austria).

A crucial part of the IFW’s identity is its vivid life including the cultivation of the scientific dialogue, family-friendly working conditions, intercultural diversity and the support of sportive and cultural activities. In 2014 the IFW organized a series of workshops, colloquia and talks to foster the scientific dialogue and, along the way, allow for social and communication aspects of cooperation. An important meeting for all scientists of the IFW was the two-day program meeting where all scientists discussed and adjusted the research program for the following year. Social events like the annual IFW Summer Day, the Christmas party and vernissages to our art exhibitions also contribute to a good working atmosphere among all IFW groups.

The positive development of the IFW is being fostered continuously by the engagement of colleagues and partners from universities, research institutes and industry, our Scientific Advisory Board and the Board of Trustees as well as the funding organizations. This holds true especially when the institute experiences turbulent times. We would like to thank all our partners and friends for their support and cooperation.
Facts & Figures

Organization
The Leibniz Institute for Solid State and Material Research Dresden (IFW) is one of currently 89 institutes of the Leibniz Association in Germany. It is a legally independent association, headed by the Scientific Director, Prof. Dr. Manfred Hennecke, and the Administrative Director, Hon.-Prof. Dr. h. c. Rolf Pfrengle.

The scientific body of the IFW Dresden is structured into five institutes, the directors of which are simultaneously full professors at Dresden, respectively Chemnitz Universities of Technology:
- Institute for Solid State Research, Prof. Dr. Bernd Büchner
- Institute for Metallic Materials, Prof. Dr. Rudolf Schäfer (temporarily)
- Institute for Complex Materials, Prof. Dr. Jürgen Eckert
- Institute for Integrative Nanosciences, Prof. Dr. Oliver G. Schmidt
- Institute for Theoretical Solid State Physics, Prof. Dr. Jeroen van den Brink

Further divisions are the Research Technology Division and the Administrative Division.

Financing
The IFW receives an institutional funding of 50% from the Federal Government of Germany and the Länder Governments each. In 2014, this funding was about 30,587 million euros.

In addition, there was a total of third party funding in 2014 of about 11,874 million euros. From that, about 37% were funded by the DFG, 31% by EU projects, 12% by Federal Government projects, 10% by industry projects and 10% by other projects and projects funded by the Free State of Saxony.
Personnel
On December 31, 2014, 506 staff members were employed at the IFW, including 114 doctorate students and in addition 22 apprentices in seven different vocational trainings. Furthermore, there was a total of 145 guest scientists and 15 diploma students working at the IFW in 2014.

Gender equality, as well as work life balance, are defined goals of the IFW Dresden. In 2014, the percentage of women in scientific positions was 34% and the percentage of women in scientific leading positions was 31%. In 2007, the IFW qualified for the certificate “audit berufundfamilie” (a strategic management tool for a better compatibility of family and career) and was already re-audited two more times.

Vocational training has always been an important activity of the IFW. At present, apprenticeships are available for seven professions. On annual average, around 25 trainees complete an apprenticeship at the IFW. In 2014, the IFW was awarded the prize “Excellent Training Company” by the German Chambers of Commerce and Industry and the institute’s apprentices received awards for their excellent performance during their training. A female physics lab technician apprentice was even nominated for the Apprenticeship Price 2014 of the Leibniz Association and achieved second place in the end. From 2012 until 2014, the IFW’s Administrative Director was the Executive Board Representative of the Dual Vocational Education and Training of the Leibniz Association.

Number of publications and patents
In terms of publications, the qualitative and quantitative level remains high at the IFW. In 2014, there were altogether 336 publications quoted by Web of science. By December 31, 2014, the IFW holds 143 patents in Germany and 155 international patents.
Research Topic 1.1

**Exotic Ground States and low-energy excitation in bulk systems**


**Responsible Directors:** B. Büchner, J. van den Brink

**Summary:** In this research topic we investigate both experimentally and theoretically a broad class of complex transition metal oxides such as cuprates, cobaltites, iridates and pyrochlore compounds, where quantum spin fluctuations, strong magnetic frustration effects and spin-orbit coupling give rise to unconventional quantum ground states and exotic spin excitations. Our research benefits a lot from a unique combination of different, mutually complementary methods that is available at the IFW Dresden, including expertise in both theory and experiment. In this article we review our work in 2014, which enabled us to obtain a number of interesting new fundamental insights into the magnetism of correlated quantum matter.

Complex transition metal (TM) oxides provide a rich playground for studies of fundamental models of quantum magnetism. In particular, in certain crystal lattices chemical bonds mediate strong magnetic exchange coupling between the spins of TM ions only in one (1D) or two (2D) spatial directions giving rise to low-dimensional spin networks in form of chains, ladders and planes. The spin chains in the 3d cuprates are considered as almost ideal realizations of the celebrated 1D spin-1/2 isotropic Heisenberg antiferromagnetic model (HAFM), since the Cu$^{2+}$ ion carries a small quantum spin-1/2 and the orbital momentum is quenched.

One focus of our research has been on the elementary excitations of a quantum spin-1/2 chain, the spinons. In our combined theoretical and experimental approach, taking spin-on excitations in the quantum antiferromagnet CaCu$_2$O$_2$ as an example, we demonstrate that femtosecond dynamics of magnetic electronic excitations can be probed by direct resonant inelastic x-ray scattering (RIXS) [1]. To this end, we isolate the contributions of single and double spin-flip excitations in experimental RIXS spectra, identify the
physical mechanisms that cause them, and determine their respective time scales (Fig. 1). By comparing theory and experiment, we find that double spin flips need a finite amount of time to be generated, rendering them sensitive to the core-hole lifetime, whereas single spin flips are, to a very good approximation, independent of it. This shows that RIXS can grant access to time-domain dynamics of excitations and illustrates how RIXS experiments can distinguish between excitations in correlated electron systems based on their different time dependence.

In the 1D spin-1/2 HAFM the spinons can be excited by an infinitesimally small energy, i.e., excitations are gapless. However, perturbations of the spin chain, such as modulation of the exchange coupling along the chain, may radically alter the spin excitation spectrum. We have shown this experimentally by measuring the longitudinal $^{63}\text{Cu}$ nuclear spin relaxation rate $T_1^{-1}$ in the model spin-1/2 chain cuprate $\text{Sr}_{1.9}\text{Ca}_{0.1}\text{CuO}_3$ [2]. Owing to the on-site hyperfine coupling, the nuclear spin sensitively probes the Cu electron spin dynamics. We observe a surprising exponential drop of the rate $T_1^{-1}$ below $\sim 100$ K which signals an opening of a pseudogap in the spin excitation spectrum, i.e., a substantial suppression of spinon excitations at low energies (Fig. 2). We attribute this drastic effect to the off-chain partial substitution of Sr by Ca which causes Cu-0 bond disorder and consequently a small random alteration of the intrachain exchange coupling. Furthermore, we can show that such bond disorder has a strong impact on the propagation of the spinons along the chain. By measuring the magnetic heat conductivity in single crystals of $(\text{Sr}_{1-x}\text{Ca}_x)_2\text{CuO}_3$ we have found that the spinon mean-free path is very sensitive to even slight bond disorder and reduces from $>1300$ lattice spacings in the clean material ($x = 0$) to very short $\sim 12$ lattice spacings for large Ca dopings [3].

Frustration effects arising in the 1D spin-1/2 HAFM due to AFM next-nearest neighbor interactions have been studied for the Cu chains in linearite $\text{PbCuSO}_4(\text{OH})_2$. Indeed we observed unusual magnetically ordered states such as helical structures together with a rich phase diagram along the Cu chain direction [4, 5]. Using DMRG and TMRG approaches we demonstrated that a significant symmetric anisotropic exchange is necessary to account for the basic experimental observations, which in turn might stabilize a triatic (three-magnon) multipolar phase [4].

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**Fig. 1:** (a) Initial state, just before the creation of the core hole. (b) Intermediate state with one doublon and one core-hole present right after the creation of the core hole. As the 3d level at the core-hole site has a net spin of 0, the magnetic coupling to neighboring sites vanishes. (c) Intermediate state just before the de-excitation of the core-hole. Left: two spins next to the core-hole site have flipped due to scattering on the doubly occupied site. Right: the spin-orbit coupling of the 2p state has flipped the core-hole spin. (d) Two-spinon excitations with $\Delta S = 0$ (left) and $\Delta S = 1$ (right) present in the final state.
Fig. 2: The $^{63}$Cu nuclear relaxation rate $T_1^{-1}$ decreases strongly below $\sim 100$ K due to the opening of a pseudogap in the spin excitation spectrum of $\text{Sr}_{1.9}\text{Ca}_{0.1}\text{CuO}_3$. Squares and closed circles correspond to measurements along the crystallographic $b$- and $a$-axis, respectively, and open circles denote our earlier data on the spin-chain compound $\text{Sr}_{0.9}\text{Ca}_{0.1}\text{O}_2$ shown here for comparison [see, F. Hammerath et al., Phys. Rev. Lett. 107, 017203 (2011)]. The inset shows the temperature evolution of the stretching exponent $\gamma$ of the nuclear magnetization decay.

Though long-range magnetic order in 1D spin-1/2 HAFM’s is not possible even at $T = 0$ due to quantum fluctuations, in real materials residual interchain couplings often induce magnetic order at finite temperatures. We have examined one specific case of the competing interchain couplings corresponding to the so-called Nersesyan-Tsvelik model in the spin-1/2 chain compound $(\text{NO})[\text{Cu(NO}_3)_2]$ [6]. Interestingly, our specific heat, neutron scattering and muon spin rotation data reveal that frustration of the interchain exchange yields incommensurate magnetic order at $T_N = 0.58$ K, much smaller than the intrachain exchange $J \sim 140$ K. A somewhat similar effect of frustration, also yielding a suppressed and incommensurate magnetic order, we have found by measuring nuclear magnetic resonance in a system with larger spin value and dimensionality, namely the non-olivine LiCoPO$_4$ [7].

The nature and the role of longer-range exchange couplings has been also explored by joint high-field electron spin resonance (HF-ESR) measurements and theoretical analysis in the 3D Cu oxide compound $\text{Cu}_2\text{OSeO}_3$ [8,9], a Mott insulator recently shown to harbor skyrmion physics. An effective model of coupled ferrimagnetic Cu tetrahedra has been derived by using exchange couplings obtained from electronic-structure computations and modeling of the HF-ESR data. It has allowed us to calculate the fundamental magnetic properties of this complex ferrimagnet, including the pitch length of the Dzyaloshinskii spiral ground state, in very good agreement with recent experiments. Additionally, a number of new predictions have been made [8]. In particular, the effective sublattices of Cu tetrahedra should display weak AF canting within each unit cell; near the ordering temperature, the magnetic phase diagram will embody a skyrmionic phase as condensates of partial skyrmions with defects in zero or low magnetic fields and a densely packed array of integer skyrmions stratified by larger applied fields.

Besides 3$d$ TM oxides, recently the 5$d$ iridates have attracted considerable attention due to predictions of novel magnetic phenomena driven by strong spin-orbit coupling. In particular, the orbital momentum of Ir$^{4+}$ is unquenched, which should lead to strongly anisotropic magnetic interactions. By HF-ESR we have studied the low-energy spin dynamics in a single crystal of $\text{Sr}_2\text{IrO}_4$, the prototype 2D spin-orbital Mott insulator. By measuring the frequency dependence of the AF resonance modes we have found a surprisingly small energy gap for magnetic excitations, amounting to only 0.83 meV [10].
This suggests rather isotropic Heisenberg dynamics of the interacting Ir$^{4+}$ effective spins, despite the spin-orbital entanglement in the ground state. The anomalous order of the Ir $t_{2g}$ levels in Sr$_2$IrO$_4$, evidenced by the structure of the $g$ tensor [10], is confirmed by electronic-structure calculations [11] and apparently related to low-symmetry potentials involving atomic sites beyond the nearest-neighbor O cage. The sizable Ir $t_{2g}$ splittings are also reflected in RIXS, e.g., in the two-peak structure of the $j=3/2$-like spin-orbital exciton. By a detailed analysis, we have further shown that this charge-neutral excitation is dressed with magnons and propagates with the canonical characteristics of a quasiparticle that mirrors the one-hole propagation in the spin-1/2 background of 2D cuprate superconductors [12]. Valuable insights into the precise structure and the magnitude of the magnetic couplings, both isotropic and anisotropic, comes from many-body quantum chemistry calculations – while in the 2D square-lattice $5d^{5}$ iridate Ba$_2$IrO$_4$, a Heisenberg-compass type of model is realized [13], the dominant interaction in 2D honeycomb systems such as Na$_2$IrO$_3$ is the Kitaev exchange, which further turns out to be ferromagnetic from the $ab$ \textit{intio} computations [14]. Joint RIXS measurements and theoretical investigations have also allowed to clarify the evolution of the magnetic excitation spectrum of Sr$_2$IrO$_4$ as function of strain [15].

Regarding the material synthesis and crystal growth, where we apply different methods ranging from flux methods (e.g., for iridates) and high pressure synthesis in the GPa regime to the travelling solvent floating zone using optical heating, we have succeeded to grow high quality single crystals of LaCuO$_2$ [16] and Li(Mn,Ni)PO$_4$ [17] which are now available for magnetic studies within this research topic.


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\textbf{Cooperation:} MPI-CPS Dresden, MPI-PKS Dresden, TU Dresden, Helmholtz-Zentrum Dresden-Rossendorf, MPI-FKF Stuttgart, Helmholtz-Zentrum Berlin, University Heidelberg, TU Berlin, TU Braunschweig, University Magdeburg, ILL Grenoble, ANSTO Australia, University Paris-Sud, University Pavia, University Tokyo, Argonne National Laboratory, PSI Villigen, ISIS, Politecnico di Milano, Moscow State University, University of Toronto, University of California Irvine, University of Crete, IISER, Pune, India
Research Area 1    FUNCTIONAL QUANTUM MATERIALS

Research Topic 1.2

Unconventional superconductivity: Mechanisms, materials & applications


Responsible Directors: B. Büchner, L. Schultz, J. van den Brink

Summary: Superconductivity as a quantum phenomenon represents one of the most fundamental problems of condensed matter physics. In spite of the long history of research there are still many new findings and open questions. Nowadays the so called unconventional superconductors are in the focus of the condensed matter community, since these materials demonstrate the highest superconducting critical temperature. In order to improve application and to find new compounds, we try to understand the nature and the key features of the emergent superconductors by means of systematic studies, both experimental and theoretical.

The following specific aspects of unconventional superconductivity are at the focus of our research:

- Symmetry and structure of the superconducting and competing order parameters
- Nature of the pairing mediator
- Competing/coexisting ground states, quantum criticality
- Pseudogap, various density waves, nematic order
- Disorder induced effects

Our research efforts seek to obtain systematic and quantitative information by applying modern experimental methods supplemented by subsequent theoretical treatment. To obtain the most precise information we use several complementary experimental techniques for the same samples. More specifically, in the experiments we use spatially and momentum resolved spectroscopies, thermodynamics, transport, magnetic resonance...
as well as phase-sensitive techniques applied together to the wide range of the single-crystalline bulk and in-situ grown thin film and heterostructured materials, such as iron-based pnictides and chalcogenides, cuprates, heavy fermion systems, ruthenates, and elemental superconductors. In theory we use a set of techniques to describe the electronic structure of superconducting materials among which are various types of Renormalization Group methods, diagramatic Green function methods, multiband Eliashberg theory and Density Functional Theory.

Our current work on the nematic order in FeSe [1] may illustrate the field of our research. It concerns one of the important aspects of all unconventional superconductors: in these materials superconductivity emerges in the vicinity to other instabilities. Therefore the understanding which of the degrees of freedom, spin, orbital or lattice, drives these instabilities, gives the answer what is the glue of superconducting cooper pairing. Most of the parent compounds of the novel iron-based superconductors exhibit magnetic spin-density wave ordering as a ground state. But the magnetic transition is preceded or coincides with the tetragonal to orthorhombic structural transition. The state in between these two transitions, which is characterized by a broken $C_4$ symmetry while time-reversal symmetry is still preserved, is called nematic.

Previously, good arguments have been put forth which rule out lattice distortions as a driving mechanism for the structural transition. Therefore it was proposed that strong spin fluctuations may lead to the nematic order. Moreover there is experimental evidence of an increase of $1/(T_1 T)$ in NMR experiments near the structural transition. However, the closeness of the two transitions (structural and magnetic) impeded an unambiguous answer to the question which degree of freedom is responsible for the structural transition.

FeSe is a unique material in that it shows only a structural but no magnetic transition and hence lends itself to the investigation of the genuine nematic phase. In FeSe, a tetragonal to orthorhombic symmetry reduction occurs at $T_{\text{nem}} = 91$ K, which is to be connected with a nematic instability. We measured NMR spectra of $^{77}$Se, having nuclear spin $1/2$, as a function of temperature in an external magnetic field $H = 9$ T. Below $T_{\text{nem}}$ we observe a splitting of the $^{77}$Se lines for $H||a$ into two lines $l_1$ and $l_2$ in contrast to the absence of a splitting for the $H||c$ line $l_3$, which hints to an in-plane symmetry change as shown in Fig. 1a depicting the temperature dependence of the Knight shift $K$. Now we discuss the possible origin of the splitting. It can be excluded that the orthorhombic lattice distortions cause the line splitting $K_1-K_2$ due to a significant change of this splitting when the superconducting state is entered at $T_c = 9.3$ K, where the lattice structure does not change notably. The in-plane orthorhombic distortion is much smaller than the $a,c$ structural anisotropy of the layered lattice structure, while the size of $K_1-K_2$ below $T_{\text{nem}}$ is of comparable size to the line splitting $K_3-K_{1,2}$ above $T_{\text{nem}}$. This is incompatible with the orthorhombic distortion being the origin of the large splitting $K_1-K_2$. The averaged $K_1$ and $K_2$ signal has the same temperature dependence as $K_3$ over the whole temperature range, while the difference Knight shift splitting $\Delta K_{l3} = (K_2-K_1)/2$ between $l_1$ and $l_2$ exhibits a typical $\sqrt{(T_{\text{nem}}-T)}$ temperature behavior of a Landau-type order parameter close to a second-order phase transition. In order to exclude spin degrees of freedom as cause of the observed in-plane line splitting we measured the spin-lattice relaxation rate as a function of temperature. The quantity $1/(T_1 T)$ probes the dynamical susceptibility and hence the antiferromagnetic spin fluctuations. However crossing the nematic phase transition it barely changes, indicating no enhancement of spin fluctuation and putting the system far away from a magnetic instability. Only when approaching the superconducting transition we find a significant
enhancement, which is evidence that spin fluctuations are not driving the nematic transition. Furthermore, the extremely narrow NRM lines well below $T_c$ indicate the complete absence of static magnetism. This leaves orbital degrees of freedom and in particular ferro-orbital order (FOO) as driver for the nematic transition. Theoretical analysis of the free energy in the vicinity of the ferro-orbital ordering transition in the presence of a magnetic field allows to derive a direct proportionality of the order parameter $\psi$ to the anisotropy in the magnetic susceptibility $\chi_{xx} - \chi_{yy} \propto \psi \propto \sqrt{(T_{\text{OO}} - T)}$. An analysis of the hyperfine constants establishes that its anisotropy and hence the anisotropy of the Knight shift difference are proportional to the orbital order parameter $\psi$: $\Delta K_{||a} \propto \sqrt{(T_{\text{OO}} - T)}$ while the averaged in-plane and the out-of-plane Knight shift depend on $\psi$ only in higher order. Clearly the measured splitting $\Delta K_{||a}$ shows a square root behavior close to the nematic transition (Fig. 1b), so that we conclude $T_{\text{nem}} = T_{\text{OO}}$. NMR does not give information about the orientation of the Fe 3d$_{yz}$ and 3d$_{xz}$ orbitals with respect to the in-plane lattice vectors a and b. However, the orthorhombic distortion induced by the FOO ordering implies an alignment of the main axis of $\chi$ with the lattice vectors: x||a and y||b, which leads to an FOO pattern aligned along either of the two in-plane axis depending on the actual domain in our twinned crystal (Fig. 1c).

![Fig. 1: Emergence of orbital-driven nematic state in FeSe.](image)
The resulting inequivalence of the a and b directions then naturally leads to the observed line splitting. A measurement of the NMR signal with the magnetic field along the [110] direction indeed does not lead to a splitting between \( l_1 \) and \( l_2 \) in the orthorhombic state below \( T_{\text{nem}} \), which is another clear proof that the tetragonal symmetry is broken below \( T_{\text{nem}} \). Finally, the significant change of the Knight shift splitting \( \Delta K_{||} \) below \( T_c \) indicates that superconductivity and nematicy are competing orders - superconductivity tends to suppress orbital ordering and vice versa.

For a more complete overview of our research during 2014 we refer the reader to our published articles, a selection of which is given in the Reference Section.


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Research Area 1

FUNCTIONAL QUANTUM MATERIALS

Summary: Our investigations on magnetic materials for energy-related applications are illustrated by several examples, which span the range from (i) fundamental research on single crystals (Mn$_3$Si), where bulk thermodynamic and transport measurements were performed to elucidate the origin of electronic ordering phenomena, over (ii) the search for new material compositions of bulk-like (Fe-Co-X) films and rare-earth-lean Sm-Co/Fe multilayers with a large magnetic anisotropy, (iii) the preparation of magneto-caloric (La-Fe-Si) composite materials with a wear close to application requirements, and (iv) studies of the micro-structural dynamics of magnetic shape-memory alloys (Ni-Mn-Ga) to (v) resolving the real structure of commercially used materials (Nd-Fe-B) at the atomic level. Related goals are (i + ii) the identification of new material compositions with potentially application-relevant properties; (iii + iv) the detailed understanding and tuning of known material classes toward specific applications; and (v) the optimization of applied materials.

(i) Spin density wave order and fluctuations in Mn$_3$Si

In many systems, there is an intimate connection between electronic ordering phenomena and unconventional superconductivity. A prime and recent example represents the class of Fe-pnictides where the suppression of the spin density wave (SDW) leads to the emergence of superconductivity. Hence, itinerant antiferromagnetic intermetallic compounds with a SDW transition may be seen as model systems for advancing the...
understanding of such electronic ordering phenomena with Mn$_3$Si being an example in the class of Heusler compounds ($T_N = 21$ K) [1] and CrB$_2$ a representative with an hexagonal structure similar to MgB$_2$ ($T_N = 88$ K) [2]. We have studied the specific heat, electrical resistivity (Fig. 1), thermal conductivity, Hall effect, Seebeck effect, and Nernst effect of a Mn$_3$Si single crystal in the temperature range from 10 K up to 300 K [1]. Clear anomalies are observed at the SDW transition in all transport coefficients. These anomalies originate in both strongly temperature-dependent changes of the relaxation time and of the Fermi-surface topology in response to the SDW transition. Moreover, we find strong evidence for a large fluctuation regime which extends up to $\sim 200$ K in the resistivity, as well as in the Seebeck and Nernst effects. This extended fluctuation regime may be interpreted as the signature of competing orders in Mn$_3$Si. A comparison of our results on Mn$_3$Si with other prototype SDW materials, viz., the iron arsenide LaFeAsO and the classical SDW prototype chromium reveals a generic manifestation of the SDW in transport coefficients.

(ii) Rare-earth-free and rare-earth-lean films with a large magnetic anisotropy

As an alternative approach to obtain rare-earth free permanent magnets we explore the suitability of Fe-Co-X films which are strained in order to induce magnetocrystalline anisotropy. For a systematic search by combinatorial methods together with RU Bochum a composition spread of epitaxial Cu-Au was examined, which allows for a large variation of in-plane lattice parameters [3]. While this approach aims to induce strain by coherent epitaxial growth, which is limited to film thicknesses of a few nm [4], the use of additional Carbon induces a spontaneous strain [5]. With this also thick films can be prepared, which reach a magnetocrystalline anisotropy up to 0.4 MJ/m$^3$.

Making use of the unprecedented magnetocrystalline anisotropy of the hexagonal SmCo$_5$ phase in epitaxial nanoscaled Sm-Co/Fe multilayer heterostructures allows the realization of record energy densities $(BH)_{max} > 450$ kJ/m$^3$ in a rare-earth-lean magnet. Figure 2 shows the dependence of $(BH)_{max}$ on the individual layer thicknesses and multilayer architecture in SmCo$_5$/[Fe/SmCo$_5$]$n$, with $n=1$ (3-layer sample) and $n=2$ (5-layer sample).
(iii) Magneto-caloric composites

Magneto-caloric La\(\text{(Fe,Si)}_{13}\) is usually very brittle and requires the combination with another material in order to form a regenerator that will survive millions of cycles in a magneto-caloric cooling device. At IFW, a novel magneto-caloric composite based on La\(\text{(Fe,Si)}_{13}\) particles in an amorphous metallic matrix has been studied [6], see Fig. 3. Magneto-caloric particles and a powdered Pd-based glass were hot-compacted at the glass transition temperature, \(T_g\), of the metallic matrix. At this temperature, the viscous matrix can easily fill the pores between the La\(\text{(Fe,Si)}_{13}\) particles, thereby creating a dense composite. Furthermore, the matrix acts as a buffer during the hot-compaction and prevents crack formation in the magneto-caloric particles, which is otherwise known to reduce their performance. Tuning our processing route, the magneto-caloric properties of the composites are almost independent of the compaction pressure.

Another possibility to form magneto-caloric composites is to combine La\(\text{(Fe,Si)}_{13}\)-based particles of various size fractions with a polymer matrix [7]. Such composites were pressed into thin plates of about 200 mm thickness, a geometry favorable for the subsequent testing of the composites in an active magnetic regenerator (AMR). We found that a higher filling factor which can be achieved by using a mixture of several particle size fractions has beneficial influence not only on the magneto-caloric properties, but also on the thermal conductivity. Tests in the AMR revealed that a maximum temperature span of approximately \(\Delta T = 10\) K under a magnetic field change of \(\mu_0 H = 1.15\) T can be obtained without cooling load. The stability of the measured \(\Delta T\) values and the mechanical integrity of the sample after cyclic application of a magnetic field have been monitored for 90,000 cycles and showed very good stability of the magneto-caloric performance.
MagKal - a good-practice-project of technology transfer

Based on the magnetocaloric effect (MCE) the efficiencies of cooling devices and heat pumps might be notably improved. Estimates of about 40% reduction in electricity consumption are tempting the industries to get early access to this new technology and to have it ready for the market launch. Keeping industrial and household applications in mind, each new technology has to compete with the established compressor cycle. Continuously improved during the last century the market is almost flooded with cheap refrigerators and heat pumps providing sufficient temperature span, thermal power and reliable operation for decades. Considering this starting point most of the research activities in the fields of magnetocalorics have to be rated concerning their contribution to further applications. The literal meaning is that materials, showing a sufficient MCE have to be at the same time mechanically stable, have to resist corrosion, and have to be available worldwide in big quantities and for low costs. Concurrently the machinery around the MCE materials has to provide efficient heat transfer into the thermal process by requiring minimal quantities of magnetic materials and less electricity than a cooling compressor. From the existing state of knowledge these challenging targets cannot be met at once. A screening process, investigating the various options of building a MCE-machine, was started in 2012 with the project “MagKal”, aiming to build an operating MCE-machine. Beyond the technical issues the market potentials of the technology should be gauged as well, so finally the project setup has to integrate all the required disciplines as depicted below:

The interdisciplinarity of “MagKal” was covered by the setup of the project team. For the material aspects and the engineering part the IFW was in charge. The Technical University Dresden contributed to the thermal issues. Finally an expert from the industries, called the innovation mentor, joined the project team for guiding the activities in terms of their relevance to the market.

The major key issues in the project are as follows:
- Finding and characterizing of alternative MCE-materials to Gd
- Identifying sufficient transfer fluid and optimization of heat transfer process
- Building of the demonstrator

During the project term quite a number of actions were taken to meet the milestones above. Some highlights are arranged exemplary below:
Funded by the Federal Ministry of Education and Research the „MagKal“-project was evaluated among 137 others and was identified as a good-practice-example. The entire project setup as well as the activities of the innovation mentor were regarded to be well determined on applying the MCE technology in niches like e.g. electro mobility. Compared to compressor refrigeration the MCE technology captivates with simple reversibility of the thermal cycle and the total absence of fluids which may harm the atmosphere. Nevertheless a real breakthrough in terms of replacing conventional compressor technologies in the mass market still needs appreciable efforts. The major key issue to be solved is still the development of sufficient MCE materials, a field on which future research activities should be focused.
(iv) Magnetic shape-memory alloys: transformation mechanisms and finite size effects

In order to understand the transformation behavior of magnetic shape memory alloys we localized the sources of acoustic emission during a martensitic transformation in collaboration with the University of Barcelona and Academy of Science in Prague [8]. Acoustic avalanches are a general feature of solids under stress, e.g., evoked by external compression or arising from internal processes like martensitic phase transformations. From integral measurements, it is usually concluded that nucleation, phase boundary pinning, or interface incompatibilities during this first-order phase transition all may generate acoustic emission. We studied local sources of acoustic emission to enlight the microscopic mechanisms. From two-dimensional spatially resolved acoustic emission measurement and simultaneous optical observation of the surface, we identified microstructural events at the phase boundary that lead to acoustic emission. A resolution in the 100-μm range was reached for the location of acoustic emission sources on a coarse-grained Ni-Mn-Ga polycrystal. Both, the acoustic activity and the size distribution of the microstructural transformation events, exhibit power-law behavior. The origin of the acoustic emission are elastically incompatible areas, such as differently oriented martensitic plates that meet each other, lamellae growing up to grain boundaries, and grain boundaries in proximity to transforming grains. Using this result, we proposed a model to explain the decrease of the critical exponent under a mechanical stress or magnetic field.

To probe finite size effects in ferromagnetic shape memory nanoactuators, together with the KIT double-beam structures with minimum dimensions down to 100 nm were designed, fabricated, and characterized in-situ in a scanning electron microscope with respect to their coupled thermo-elastic and electro-thermal properties [9]. Electrical resistance and mechanical beam bending tests demonstrate a reversible thermal shape memory effect down to 100 nm. The comparison of surface and twin boundary energies allow to explain why free-standing nanoactuators behave differently compared to constrained geometries like films and nanocrystalline shape memory alloys.

(v) Interfaces in Nd-Fe-B magnets at the atomic scale

The crystal structure and chemical composition of interfaces in Nd-Fe-B magnets has been studied at unprecedented spatial resolution using a combination of aberration-corrected scanning transmission electron microscopy (STEM) and electron energy loss spectroscopy (EELS). These techniques allowed variations in the concentrations of minor alloying elements near the surfaces of the Nd$_2$(Fe,Co)$_14$B grains to be detected on the atomic scale [10]. Figure 4 shows EELS elemental profiles overlaid on the corresponding image.
corresponding high angle annular dark field (HAADF) image. The image shows a grain of Nd$_2$(Fe,Co)$_{14}$B on the left and the interface to an intergranular phase on the right. The last vertical line of bright points from the left is the terminating plane of atoms of the Nd$_2$(Fe,Co)$_{14}$B grain. Enrichment of Co in the outermost unit cell of the Nd$_2$(Fe,Co)$_{14}$B and interfacial segregation of Cu were observed (Fig. 4). Co is known to have a detrimental effect on the coercivity of the material but such local concentrations have not been previously observed. Molecular dynamics simulations of grains with and without Co enrichment at the surface showed that the magnetoelastic anisotropy was reduced in the Co enriched region. This is also likely to have a detrimental influence on coercivity. The results contribute to the fundamental understanding of coercivity in Nd-Fe-B magnets and may be used to guide experiments in enhancing coercivity in future materials.


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Research Topic 1.4

Engineering magnetic microtextures


Responsible Directors: B. Büchner, O. G. Schmidt, L. Schultz, J. van den Brink

Summary: The unique properties of non-trivial topological states, e.g. magnetic skyrmions [1] may path the way towards novel spintronic devices [2]. However, these spin textures have only been observed in special classes of materials possessing non-centrosymmetric crystal structure [1, 3-6] and at low temperatures, which limits their application potential. Within research topic 1.4 we focus on realizing novel and configurable inhomogeneous magnetization states such as skyrmions and chiral domain walls at room temperature and on their thorough static and dynamic study. Effort is dedicated to the search of appropriate magnetic phases by first-principle calculations, to the preparation of coupled multilayer systems with chiral magnetization states and their investigation by magnetic x-ray and Kerr microscopy, and to the further development of optical and scanning probe microscopy techniques for an improved characterization of magnetic microtextures on variable length and time scales. The following examples summarize the progress in the theoretical description of chiral helimagnets, in the realization of chiral magnetization states imprinted into Co/Pt/Py multilayers and in new developments in magnetic force microscopy (MFM), namely depth resolved quantitative MFM and a new sensing concept based on coupled oscillators.

Search for skyrmionic states and phases in chiral helimagnets

Search for skyrmionic states and phases in chiral helimagnets remains a challenge, owing to the specific requirements on symmetry and secondary magnetic properties like magnetic anisotropies and magneto-elastic couplings. With a combination of theoretical and computational approaches we predict these properties in magnetic materials to guide and support this search. In cooperation with external experimental groups we have performed studies on the transition metal germanides FeGe and MnGe with
B20-structure, which are the archetypical chiral cubic helimagnets. In both materials, the application of high pressure allows to reach unconventional magnetic states near the collapse of magnetic order, while evidence for skyrmionic states exists for both compounds also at ambient pressure. A combination of neutron scattering experiments, magnetic measurements, and ab initio calculations uncovered an evidence for a spin-state transition in MnGe from a high-spin to a low-spin transition under hydrostatic pressure [7], an effect that has been predicted by us earlier. In future, it remains to be seen whether the helimagnetism of MnGe with an uncommonly short and temperature-variable period at ambient pressure can be explained by the proximity of the magnetic system to this spin-state transition. In the classical chiral helimagnet FeGe, a Mössbauer experiment under pressure shows the existence of an inhomogeneous chiral magnetic precursor state [8]. In this quasi-static state reached without proper phase transition from the paramagnetic side, the longitudinal magnitude of the spin-density is inhomogeneous and quasi-static on the time-scale of the Mössbauer experiment. The experiment provides important evidence for the unconventional type of magnetic ordering transition via intermediate mesophases in chiral helimagnets. The interpretation of the experimental results required a detailed calculation for the evolution under pressure of the hyperfine parameters in FeGe by density-functional theory calculations using the in-house FPLO-code.

We have started a cooperation with groups at the Max Planck Institute, CPFS Dresden to analyse tetragonal Heusler-type compounds of type Mn2YZ. In these systems, ferrimagnetic or canted spin-structures with large non-collinear order and co-existence of ferromagnetic and antiferromagnetic order-parameters in bicritical phase-diagrams are combined with the existence of inhomogeneous Dzyaloshinskii-Moriya-couplings. These complex and versatile systems promise novel types of skyrmionic states [8]. In particular, the specific low symmetry of these compounds should allow to realize the field-induced hexagonal skyrmion lattices that should be named Bogdanov-Hubert-phase following the first prediction of this condensed skyrmion phase in the ground-state of phase-diagram of chiral helimagnets in absence of competing conical helix-phases.

Magnetic chiral spin textures via imprinting

We offer an alternate route to design synthetic magnetic heterostructures that resemble swirls, vortices or skyrmions with distinct topological charge densities at room temperature. By vertically stacking two magnetic nanopatterns with in- and out-of-plane magnetization and tailoring the interlayer exchange coupling, non-collinear spin textures with tunable topological charge can be imprinted (Fig. 1a).

The concept is demonstrated on nanostructures consisting of soft-magnetic 40 nm thick Permalloy (Py, Ni80Fe20) and 5 nm thick Co/Pd multilayers. First, we conduct systematic micromagnetic simulations of the magnetic spin texture in a disk-like heterostructure with a diameter of 400 nm where the interlayer exchange coupling strength between Py and Co/Pd sub-systems is varied from 0.1 to 2 mJ/m². In strongly coupled heterostructure, the magnetic state of the Co/Pd is determined by the spin configuration in the Py disk resulting in the in-plane circulation of the magnetization thus resembling magnetic vortex state (Figs. 1b,c). At an intermediate coupling strength, remanent donut states with a central vortex within the Co/Pd layers occur. Driving full or minor hysteresis loops allows to stabilize topologically distinct donut states with topological charges of about 1 and 0. The resulting magnetic configuration of the donut state, achieved at remanence after saturating the sample, is similar to those found in a disk with Dzyaloshinskii-Moriya interaction [10] hence suggesting that skyrmion-like structures can be experimentally realized in exchange coupled heterostructures. Owing to the larger switching field of the vortex core compared to the surrounding Co/Pd spins, the reversible switching between these states can be achieved. In this way, the topological charge can be switched in a digital manner at room temperature and at zero field.
As our concept does not rely on vortex polarity switching in contrast to [11], much lower static magnetic fields are needed to manipulate the topological state of the material. We have experimentally studied the magnetization reversal process and magnetic domain patterns in nanostructured [Co/Pd]/Pd/Py stacks sputter deposited onto assemblies of non-magnetic silica spheres with a diameter of 500 nm. The Pd spacer thickness is varied from 1 to 30 nm. Evidence for the stabilization of non-collinear spin textures in the Co/Pd layers is provided by direct imaging of the magnetization patterns utilizing X-ray magnetic circular dichroism (XMCD) with high resolution magnetic soft X-ray transmission microscopy (MTXM) and X-ray photoemission electron microscopy (XPEEM). For a 1 nm spacer thickness a vortex structure is observed (Fig. 1c), in agreement with theoretical predictions. At 3 nm spacer thickness, an out-of-plane component appears in the Co/Pd sub-system. However, the circulation of the in-plane magnetization component still remains. For this sample, we clearly identify formation of different donut states as well as multi-domain states (Fig. 1e). The experimentally resolvable in-plane XMCD contrast in Co/Pd stack vanishes for the sample with 5 nm spacer thickness. The core of the imprinted vortex in the Co/Pd multilayer is enlarged (60–110 nm) with respect to the Py vortex core due to the additional intrinsic out-of-plane anisotropy of Co/Pd.
Magnetic vortex observation in FeCo nanowires by quantitative magnetic force microscopy (qMFM)

An approach is presented that allows quantifying the three dimensional magnetization pattern of a magnetic nanoobject from measured two dimensional magnetic force microscopy (MFM) data. It is based on (i) a MFM deconvolution approach, which quantitatively characterizes the imaging properties of a MFM tip at a given height above the sample surface (tip transfer function) [12, 13], (ii) on a micromagnetic calculation of the total magnetic charges of the magnetic nanoobject and a projection of the lower lying charges onto the sample surface, (iii) a convolution of the such obtained effective surface charges with the tip transfer function to obtain a theoretical MFM image, and (iv) a comparison with the experimentally measured MFM signal.

By making use of the depth sensitivity of MFM and by applying a quantitative contrast analysis, we are able to reconstruct the inhomogeneous magnetization state at the end of individual cylindrical Fe52Co48 nanowires arranged in a triangular array. Figure 2 shows an experimental top-surface MFM image of a CoFe nanowire array in its demagnetized state with arbitrary magnetization state (either up or down) along the length of each nanowire, visible from the dark or bright contrast. A surface charge model is convolved with the tip transfer function (TTF) of the previously characterized MFM tip, resulting in a theoretical MFM pattern. Assuming a homogeneously magnetized nanowire with appropriate saturation polarization overestimates the measured signal by a factor of 2 (not shown here). Including the magnetization vortex at the very end of the nanowires as derived from micromagnetic calculations not only leads to a very good qualitative but also to a perfect quantitative agreement. This is the first experimental proof of the vortex state at the end of an embedded magnetic nanowire [14].

Fig. 2: Calculated MFM signal (top right) in comparison with experimental MFM signal (bottom right) of a CoFe nanowire array. The effective surface charge model (top left) is based on the visible magnetization orientation within each nanowire and the precise charge profile derived from micromagnetic simulations (bottom left).
Nanomagnetic probes and magnetometers based on coupled oscillators

We developed a concept of coupled mechanical oscillators consisting of a nanowire oscillator (2) attached to a micron-sized oscillator (1) with tuned eigenfrequencies of the individual oscillators (Fig. 3). Applied to cantilever magnetometry and magnetic force microscopy, such coupled systems constitute very sensitive probes. This concept has been confirmed by simulations (Fig. 3) and first experiments.


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Strong correlations in Chern bands

The recently discovered prospect of realizing fractional quantum-Hall (FQH) states with the inclusion of short-range interactions in lattice models has garnered considerable interest. Apart from a paradigmatic extension of the FQH effect to lattices, these states, called fractional Chern insulators (FCI), arise without an externally applied magnetic field. Hence, they are an important conceptual step towards potential technological applications.

There are already several proposals for the realization of FCI states, some of which involve optical lattices, while others are based on known material structures, such as strained or irradiated graphene, oxide heterostructures, or layered multi-orbital systems proposed by our group [1, 2]. The latter category is particularly promising, since the energy scales at which the desired physics emerges is of the order of room temperature.

Since their inception, FCI states have been studied with various numerical and analytical methods. Of particular interest are works that emphasize the differences between FCI states and traditional FQH physics. The most obvious difference is that Chern bands, unlike Landau levels, have a non-vanishing dispersion. In an earlier work, we have proven by example that this dispersion may actually favor FCI states [2]. Unlike FQH systems, FCI models can be naturally extended to include both spin species, and it has been shown that the resulting time reversal-symmetric models can be hosts of fractional topological insulators. Since the Chern number of a band can, in contrast to a Landau level, take values larger than one, FCI states can occur in partially filled bands with higher Chern numbers. Finally, topologically ordered states that go markedly beyond the Landau-level picture, in which the topological character is combined with Landau-type order, have been found by two of us recently [3].
If one wishes to search for FCI states in the laboratory, understanding of how these states can arise in realistic multiband systems is crucial. In Ref. [4], we pose two fundamental questions for the realization of FCI states, namely (i) whether the mixing of bands by interactions leaves space for FCI states to arise, and (ii) whether FCI states can be found far beyond the energy scale of the band gap. To this end, we have studied two prototypical two-sublattice FCI models using exact diagonalization, taking both Chern bands into account [4]. We show that FCI states survive band mixing caused by arbitrarily large interactions. To demonstrate this, we introduce the extreme limit of nearest-neighbor interaction going to infinity. In this regime, particles dressed by the interaction form extended objects, which can be interpreted as non-interacting hardcore particles occupying more than one lattice sites. We find that strong interactions of magnitude far larger than the band gap may actually favor FCI states, regardless of whether the bands are mixed, see Fig. 1.

Within the FCI regime (the colored part of the phase diagrams in Fig. 1), the ground-state eigenvalues exhibit the empirical characteristic features of FCI states: 3-fold degeneracy and spectral flow. In order to establish beyond doubt that the phase is indeed an FCI, we calculate the Hall conductivity in this regime and find it to be very precisely quantized to the value $-1/3$ [4].

In [3], we go beyond the limit of „weak” interactions, into a regime where different Chern bands mix. We find states that show the features of both a CDW and of an FCI and, thus, arrive at an exotic state of matter that is characterized by both Landau-type and topological order and is understood in terms of both band topology and lattice geometry. This novel class of states can be intuitively understood as comprising of particles that play two roles simultaneously. Most of them form the CDW occupying 1/3 of the triangular lattice sites, see Fig. 2(b). Additional particles can then move on the remaining sites, up to a total density of $n = 2/3$ (two fermions per three lattice sites). One can view the remaining sites as an effective honeycomb-lattice model, which has here a 4-site unit cell, see Fig. 2(b), and is described by topologically nontrivial hoppings.

Fig. 1: Phase diagrams of (a) the triangular and (b) the checkerboard lattice models on a 48-site cluster at $\nu = 1/3$, $V_1 = \infty$ in the plane spanned by the chemical potential $\mu$, and the third nearest-neighbor hopping $t_3$. The color coding is the lowest value of the gap between FCI ground states and excited states upon flux insertion. The dashed white line in (b) denotes the phase boundary for the non-interacting model.

Fig. 2: Charge density wave (CDW) and fractional Chern insulator (FCI) on the triangular lattice at a density $n = 1/3$. (a) Phase diagram of the model used in Ref. [3] for a 3 x 3 unit-cell (6 x 3 lattice-site) system with 6 fermions and only nearest-neighbor repulsions $V_i$. (b) The 4 x 4 - 1 = 15 unit-cell (30 lattice-site) cluster used in Ref. [3]: the unit cell (black/red circles), the charge-order pattern (filled circles) arising in the CDW and the hoppings. Solid, dashed and arrowed black lines represent complex hoppings $t$ with phases of 0, $\pi$ and $\pm \pi/2$, respectively. Grey lines denote hoppings deactivated by the CDW. Third nearest-neighbor hoppings $t'$ are not shown.
The eigenvalue spectra of our interacting spinless-fermion model on the triangular lattice at filling fractions $\nu = 12/15$ and $13/15$ hint at ground states that are neither FCI nor CDW, but have features of both. The Landau order, commensurate charge modulation in the ground states, reveals itself in the interaction strength-dependent peaks in the static charge-structure factor. The topological order is established via the Hall conductivity, which is precisely quantized, but with a value $\sigma_H \neq \nu$. Instead, we find a quantization consistent with viewing the ground states as composites of a CDW state and a FCI state formed by additional particles in the part of the lattice that remains unoccupied by the CDW [3].


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Summary: The most prominent characteristic of non-equilibrium materials is the energetically unfavourable state they have adopted during their synthesis. The entire microstructure or parts of these materials are in structural, compositional or morphological metastability, which defines their unusual and interesting mechanical, chemical and physical properties [1]. Some of the eldest and probably best-known examples comprise silicate glasses or martensite formation in steels.

A wide variety of other, novel non-equilibrium materials are the objects of the research conducted in research area 2.1. The present report shall give a glimpse of the diversity of materials and methods used to obtain and to characterise them. Therefore, as a cross section, this treatise covers bulk metallic glasses (BMGs), BMG matrix composites, cryomilled, nanostructured Cu as well as heavily deformed metals and alloys.

Strain determination in a metallic glass by X-rays

Understanding the deformation mechanisms in metallic glasses is a very challenging task. The structural entities, which govern deformation in metallic glasses (shear transformation zones, STZs), are of very small size and cannot be unveiled directly [2,3]. However, diffraction using high-energy X-rays is capable of revealing details of the structure, which allow the determination of the local strain state in the glass [4,5]. That way, the occurrence of shear bands, which result from the coalescence of STZs, can be better understood and their formation can be correlated with the local strains—or the structure.

Here, the surface of a Zr_{52.5}Ti_{15}Cu_{18}Ni_{14.5}Al_{10} bulk metallic glass was structured by imprinting a line pattern with a steel mould at room temperature [6]. This forces the glass to deform plastically and leaves periodic grooves at the surface (Fig. 1). The sample was then scanned with a high-energy X-ray beam (Fig. 1) and the local strains were calculated from the shift of the first diffraction maximum [4,7].
The three components of the strain tensor ($\varepsilon_{xx}$, $\varepsilon_{yy}$, $\varepsilon_{xy}$) were determined for each point to create spatially resolved strain maps. Figures 2(a) - 2(c) show the strain components, which are negative for compressive and positive for tensile strains. Characteristic patterns of alternating tensile and compressive strains are obtained. Especially the in-plane strains ($\varepsilon_{xy}$) are rather pronounced. A comparison between the medium-range order (MRO, first diffraction maximum) and the short-range order (SRO, higher order maxima) suggests a significant structural anisotropy. The shear strains in Fig. 2 are much larger than the elastic shear components obtained from X-ray experiments during uniaxial loading, which are close to zero [4,8]. The shear band pattern after deformation of the imprinted BMGs clearly proves that the generation of shear bands is governed and affected by these residual strains.

**Steel spring-metallic glass composite**

Monolithic bulk metallic glasses tend to fail in a brittle fashion [9]. The reason for this is the formation of shear bands already mentioned above. Once they form, the glass becomes softer and the shear bands preferentially transform into cracks [2,9]. One way to overcome this limited damage tolerance is to incorporate a second, crystalline phase [10,11]. The crystalline phase interacts with the formation of these shear bands and aggravates their propagation and thus retards fracture [10].

A special case of such a composite is shown in Fig. 3: a steel spring of a ball pen was infiltrated by a glass-forming Zr$_{52.5}$Ti$_{15}$Cu$_{15}$Ni$_{10.5}$Al$_{10}$ melt (inset in Fig. 3) [12]. The longitudinal cut of this sample shows the glassy matrix and the relatively darker steel spring (Fig. 3). Even though the wetting of the spring is not always sufficient (voids in Fig. 3) the plasticity can be significantly enhanced as the compression tests prove (Fig. 4 (a)). The strength of the composite is somewhat lower but this sacrifice is counterbalanced by a substantial increase in the plastic deformability. Moreover, the dynamics of the shear banding process are altered due to the presence of the steel spring. Relatively large stress drops followed by elastic loading are observed in the case of the as-cast metallic glass (Fig. 4 (b)). In contrast, much more serrations appear in the spring-glass composite and the energy release for each serration is also much smaller.
Nanostructured Cu through cryomilling

The metallic glasses mentioned above were all obtained via quenching of a melt. Another route to obtain glasses for instance is ball milling [1]. Depending on the powder composition and the milling parameters not only metallic glasses can be synthesised but also nanocrystalline metallic materials [13]. In this context, it is crucial to understand the mechanisms as of how the nano-scale microstructure evolves. This can be done by detailed X-ray diffraction line analysis coupled with high-resolution transmission electron microscopy (TEM) [14].

The grain size for cryomilled Cu obtained by TEM ranges between 10 and 200 nm (Fig. 5(a)). This is different compared to the size distribution obtained by XRD because for deformed Cu XRD provides the size distribution of dislocation cells, while TEM gives the grain size distribution. There is no sign of discontinuous dynamic recrystallisation (DDRX). Microstructural refinement occurs via dislocation activity including dislocation generation and accumulation, annihilation and recombination of dislocations to form dislocation cells, and gradual conversion of the dislocation cells to individual grains.

Cu-Zn15, however, has a reduced stacking fault energy and contains very small grains with size in the range of 5 -10 nm within a heavily strained matrix made of larger grains (50 - 150 nm) (Fig. 5(b)). These grains are due to the occurrence of DDRX. Dynamic recovery is inhibited and dislocation density reaches a critical value at which dynamic recrystallisation may initiate. Both structural decomposition and dynamic recrystallisation are responsible for nanostructure formation during cryomilling of Cu-Zn alloys.

Phase transformation kinetics

The formation of phases from non-equilibrium conditions as e.g. heavily deformed metallic materials and composites is a measure of the phase stability of the non-equilibrium state in terms of the variables of state and time. At the same time the irreversible transformation from one state to another is comprised by a change of the microstructure. Hence, it is of great importance to detect and understand microstructural changes as well as to link them to the underlying mechanisms. Such transformations can readily be detected by in-situ R(T) measurements, as e.g. the formation of intermetallic phases such as TiAl from pure elements of recrystallisation processes as described below. As mentioned before, the microstructure of single-phase copper alloys can be altered by cold deformation. Depending on the processing parameters like temperature or the stacking fault energy, the dominant deformation mechanism is different and the refinement of the microstructure bears other rates with respect to the deformation strain. The formation of deformation twins is activated at low homologous temperature or at low...
Research Area 2 FUNCTION THROUGH SIZE

stacking fault energy leading to smaller grain sizes achieved at a certain deformation strain. Figure 6 shows the microstructures of Cu-Al alloys after deformation at cryogenic conditions and the results of in-situ resistivity measurements. The resistivity changes associated with microstructural changes during recovery and recrystallisation during heating are highlighted by the derivative of the resistivity with respect to the temperature. Deviations of $\frac{d\rho}{dT}$ from this $\rho_0\alpha$ value indicate changes of the densities of defects acting as scattering centres for electrons.

Lowering the temperature during deformation causes a significant reduction of the characteristic temperature when compared to the deformation at room temperature.

**Fig. 6:** Microstructure of Cu, CuAl1 and CuAl3 after deformation at cryogenic conditions and the derivative of the resistivity with respect to the temperature.

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**Cooperation:** University of Vienna, Austria; University of São Carlos, Brazil; University of Cambridge, United Kingdom; University of Turin, Italy; Harbin Institute of Technology, People’s Republic of China; Edith Cowan University, Perth, Australia; Indian Institute of Technology (BHU), Varanasi, India; Yonsei University, Seoul, Korea; Tohoku University, Sendai, Japan
Summary: The key concept of this research topic is to define new routes for creation of tailored metallic materials based on scale-bridging intelligent hybrid structures enabling property as well as function optimization. The novelty - as compared to conventional ideas - is that they apply to monolithic amorphous or bulk (nano-)microcrystalline materials. The basis is founded on innovative strategies for the design, synthesis and characterization of intrinsic length-scale modulation and phase transformation under highly non-equilibrium conditions. This includes the incorporation of dispersed phases which are close to or beyond their thermodynamic and mechanical stability limit, thus forming hierarchically structured and ductile/tough hybrid alloys. Alternatively, the material itself is designed in a manner such that it is at the verge of its thermodynamic/mechanical stability.

Deformable soft-magnetic bulk metallic glasses (BMGs)

Ferromagnetic Fe- and (Fe,Co)-based amorphous alloys are regarded as attractive industrial alloys due to relative low price and simple routes for fabrication. Within several new BMGs developed in the last decade, the \([\text{Fe}_{0.5}\text{Co}_{0.5})_{0.75}\text{Si}_{0.05}\text{B}_{0.20}]_{96}\text{Nb}_{4}\) glassy alloy plays an important role because it combines a high glass-forming ability (GFA) with good soft-magnetic properties and very high compressive strength. However, a major drawback of almost all Fe- and (Fe,Co)-based BMGs, which hinders their application, is the absence of sufficient plastic deformation. Generally, the routes used to enhance the deformability of glassy alloys point towards creation of a composite structure or designed heterogeneities, for example, through mechanical pre-loading or severe plastic deformation. These methods must be applied eventually with caution to Fe- and (Fe,Co)-based alloys, because the soft magnetic properties can deteriorate in the presence of non-magnetic crystalline phase(s) or due to the stress induced by mechanical treatment. A solution for magnetic BMGs can be fine-tuning the composition by adding element(s) with large Poisson ratio such as, for example, Ni or minor additions of Cu. By adding 0.5 at.% Cu to the aforementioned composition we created - for the first time - a FINEMET®-type BMG with enhanced deformability [1]. Monolithic samples with 1 mm
diameter revealed a fracture strain of 3.80% and a maximum stress of 4143 MPa upon compression, together with a slight work hardening-like behavior. The soft magnetic properties are preserved upon Cu-addition and the samples show a saturation magnetization of 1.1 T combined with less than 2 A/m coercivity. The Cu-added glasses show a very good thermal stability but, in comparison with the base alloy, the entire crystallization behavior is drastically changed [2]. Upon heating, the new glassy samples show two glass transition-like events, separated by an interval of more than 100 K, in between which a BCC-(Fe,Co) solid solution is formed. This unique behavior was investigated by time-resolved X-ray diffraction in transmission configuration, using a high-intensity high-energy monochromatic synchrotron beam at the ID11 beamline at ESRF Grenoble, France. The patterns presented in Fig. 1 start at 794 K, i.e. in the supercooled liquid region of the initial fully amorphous and homogeneous BMG sample and finish at 910 K, within the supercooled liquid region of the remaining amorphous matrix. The crystalline peaks superimposed to the amorphous background are characteristic for a BCC-(Fe,Co) solid solution. By appropriate control of the size and distribution of the nanograins this behavior can be further exploited for enhancing the soft magnetic properties as well as the plastic deformability even more.

**BMG-Matrix Composites with crystalline TRIP/TWIP particle reinforcement**

It has been shown that crystalline inclusions or precipitates can enhance tensile plasticity of the BMGs. One general approach is to arrest single localized shear bands and/or to disperse the material reaction into multiple shear banding in order to retard failure. With the background of Twinning Induced Plasticity (TWIP) and Transformation Induced Plasticity (TRIP) [3-5] it is envisaged to create new BMG-Matrix Composites that have an active component as second phase. This approach has already been proven to be successful by using the formation of B2 CuZr-type particles within an amorphous CuZr-based matrix [6] that show work hardening and interact with shear bands by deformation twinning and martensitic phase transformation. We extended this approach by producing BMG-Matrix Composites through Selective Laser Melting (SLM) [7]. Here, Fe-based amorphous powders that have been successfully processed by SLM [7] into bulk amorphous samples were mixed with powders from Shape Memory Alloys (SMA) and co-processed via SLM into BMG-Matrix Composites. Within the active temperature range of the SMA, similar beneficial effects on the mechanical properties of the BMG matrix are expected as stated above. First tests show that bulk structures can be additively manufactured from mixtures of Fe74Mo4P10C7.5B2.5Si2 (at.%) gas atomized amorphous powder and a Cu-11.8Al-3.2Ni-3.0Mn (wt.%) SMA powder by the SLM technique. Fig. 2 shows hollow cylinders with 4 mm diameter and 8 mm height processed via SLM from a 9:1 mixture of a Fe74Mo4P10C7.5B2.5Si2 (at.%) gas atomized amorphous powder and a Cu-11.8Al-3.2Ni-3.0Mn (wt.%) SMA powder: (a) using the set of parameters adapted to the SLM of the Fe-based powder as in [7], (b) improved set of parameters adapted to the SLM of the Cu-based SMA.
mixture of these FeMoPCBSi gas atomized amorphous and CuAlNiMn SMA powders manufactured using (a) a SLM set of parameters adapted to the processing of Fe-based powder [7] and (b) an improved set of parameters, adapted to the SLM of the Cu-based SMA. The properties of these composites are currently investigated.

Development and study of Co-based metallic glasses and composites

Another subject of the INTELHYB research topic focuses on the development and study of novel high-strength and soft-magnetic Co-based metallic glasses and composites. Since direct casting of these materials into rods is very challenging and mostly unsuccessful, other techniques like melt-spinning and gas-atomization were applied as the pre-processing steps. The investigated melt-spun Co46Hf6.5B27.5, Co42Fe10Hf6.5B27.5 and Co40Fe22Hf6.5B31.5 (at. %) amorphous ribbons exhibit average thicknesses in the range of 18 to 67 μm, and band widths between 1.5 and 4 mm depending on the chamber pressure, the wheel speed and the casting temperature. So far, the best surface quality and highest bend fracture angle (as a first indicator for ductility) was achieved for Co42Fe10Hf6.5B27.5 ribbons. Fig. 3(a) shows an as-spun 1.5 mm wide Co42Fe10Hf6.5B27.5 ribbon which exhibited the best deformability. The ribbon is very uniform and ductile. Yet, there are still demands for optimization with respect to the sample dimensions for potential future applications.

Co40Fe22Ta8B30 and Fe-based reference materials were gas-atomized by ejecting the molten metal via a dual in-house upgraded water/Ar jet system, and finally quenching in water. The powders have a narrow particle size distribution between 100–150 μm for a nozzle slit-size of 700 μm. Fig. 3(b) shows a snapshot of the atomization process of the Co40Fe22Ta8B30 alloy. One can observe the central stream of the molten alloy which is further spread at the intersection of the water jet (the laminar jet in the picture coming out from the left nozzle) and the symmetrical Ar gas jet (invisible here, coming out from the right nozzle). The powder is collected in a water-filled tank placed below the atomization point. According to DSC and XRD measurements, the spherical Co-based particles are coated by an oxide layer. Therefore, additional manufacturing steps such as ball milling and chemical treatment (e.g. etching) are necessary to confirm amorphization of the inner core material.

As a future prospect, melt-spinning will be applied to the new master alloy family, (Co48.8B28Si12.2)96Hf4 and (Co48.8B25.7Si5.7)96Hf4, whose stoichiometry is attributed to the cluster line approach for the ternary Co–B–Si system. In general, hafnium is used to increase the glass-forming ability and bonding strength, however it has a high affinity to residual oxygen in the environment, as already observed by first injection/suction casting and gas atomization tests. Based on the principle from previous research works [8–10], granules or flakes made of ball-milled amorphous ribbons and gas-atomized amorphous powders can be used for different consolidation processes. Future activities will consist of hot forming and selective laser melting of Co-based feedstock to investigate the mechanical and structural properties of bulk glassy samples and composites.

Fig. 3: (a) As-spun 1.5 mm wide very uniform and ductile Co40Fe22Ta8B30 ribbon showing the best deformability. (b) Snapshot of the atomization process of the Co40Fe22Ta8B30 alloy. The central stream of the molten alloy is further spread at the intersection of the water jet (the laminar jet in the picture coming out from the left nozzle) and the symmetrical Ar gas jet (invisible here, coming out from the right nozzle). The powder is collected in a water-filled tank placed below the atomization point.
Molecular dynamics simulations of the deformation behavior of metallic glass composites

Many literature results in the field of BMGs and their composites were obtained upon “trial and error” methods. The INTELHYB research project aims to study in-depth the theoretical aspects of the mechanical behavior with the help of mathematical models. Therefore special efforts are focused towards theoretical design and optimization. By computer simulations we provide detailed insights into the structure and properties of metallic glasses and composites at the atomic level.

As discussed previously, in case of monolithic BMGs the plasticity is localized in a few dominant shear bands, as displayed by the red colored spots (which indicate the stress concentration) in Fig. 4(a). One of these shear bands can go critical resulting in brittle failure of the material. In order to improve the mechanical properties of metallic glasses a promising way is to form composites containing a secondary crystalline phase. We simulated the deformation mechanism of a Cu₆₄Zr₃₆ metallic glass composite in form of a laminate embedded between two B2 CuZr crystalline plates which may undergo stress-induced martensitic transformation. Fig. 4(b) refers to this situation. Upon tensile deformation, above a critical stress level, the crystalline plate undergoes a martensitic transformation from B2 (blue atoms in the picture) to FCC phase (green atoms in the picture). When the crystalline plate and the metallic glass are joined together a new hybrid structure is formed, which shows a completely different mechanical behavior (Fig. 4(c)). First, the plasticity in the glassy phase is no more localized in one dominant shear band as in the case of bulk glass. Many shear bands form (red colored spots) and they try to avoid those areas where the crystalline plates exhibit martensitic transformation (here colored in grey). In other words, there it is a strong competition between the glassy and crystalline phases to accommodate the elastic energy. Moreover, it seems that the residual elastic energy is not large enough to induce a transformation from the B2 to FCC phase as found for crystalline plates. Rather, the crystalline plates transform from the B2 to the tetragonal phase (Fig. 4(c), marked with gray spots) and this transformation follows the 45 degree shearing direction. All these preliminary results provide clear evidence that the mechanical properties of composite materials can be tuned by controlling the crystalline fraction, phase, orientation, size, geometry, etc. Further studies will be conducted to provide a clear understanding of the deformation behavior of hybrid materials and to improve the ductility of this class of materials.

Fig. 4: Molecular dynamics simulations of the deformation mechanism of a bulk metallic glass (a), a B2 crystalline plate (b) and a composite structure formed by joining both of them (c). All samples are deformed in tension with a strain rate of $4 \times 10^7 \text{ s}^{-1}$ at 50 K.


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**Research topic 2.3**

**Multifunctional inorganic nanomembranes**

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**Responsible Directors:** O. G. Schmidt, J. Eckert, L. Schultz, J. van den Brink

**Summary:** Inorganic nanomembranes are flexible and can be transferred to virtually any substrate. This allows for transforming rigid electronic elements into their flexible counterparts with the goal to make consumer electronics thin, lightweight, and compliant. We aim at (i) understanding the electronic, magnetic, and optical properties of thin films with tunable curvature and (ii) realizing electronics with multiple diagnostic and communication capabilities at different length scales from large area wearable electronics down to compact Lab-in-a-Tube devices.

**Stimuli responsive microjets:** Artificial micromotors offer great possibilities for research spanning from fundamental mechanisms of motion [1-3] at the micro- and nanoscale to potential biomedical [4-7] and environmental applications [8-10]. In collaboration with Ionov’s group from the Institute for Polymer research, IPF Dresden, a new kind of flexible artificial micromotor was demonstrated (Fig. 1) [11]. In this case, thermoresponsive microjets are generated from two layers of polymers (polycaprolactone and poly(N-isopropylacrylamide)) with a thin inner platinum layer which form a microtube upon release from the substrate. These self-folding micromotors move autonomously due to the catalysis of hydrogen peroxide on the platinum surface. The flexible microjets can reversibly fold and unfold by applying changes in temperature. This effect allows the microjets to rapidly start and stop multiple times by controlling the folding of the microjet. This new approach offers a convenient speed control mechanism during the operation of catalytic micromotors and is especially interesting for studies on bubble formation inside tubes.

**Fig. 1:** Flexible self-propelled microjets are formed by temperature-induced folding of thin polymer films into microtubes that contain an inner platinum layer for catalytic bubble propulsion in hydrogen peroxide. The polymer films are bilayers of an active and a passive component, which cause the microjets to fold and unfold reversibly by applying slight temperature changes. The speed control by shaping the polymeric Pt films offers a unique approach to operate this new kind of flexible bubble-propelled micromotors. The image is taken from V. Magdanz et al., Angew. Chem. 126, 2711 (2014).
Vortex dynamics influenced by pinning centers and collective phenomena in superconductor microtubes: Dynamics of superconducting vortices in micro- and nanostuctures are determined by a number of interplaying factors, including geometry, pinning centers and collective phenomena. We have demonstrated that detection of curvature effects on vortex dynamics [12] stays feasible in the presence of the pinning centers. The impact of pinning centers on vortex dynamics on Nb superconductor open microtubes [13] (Fig. 2a) has been analyzed. Certain regions on a tube have been revealed, where the presence of pinning centers is especially significant for vortex dynamics (Fig. 2b). The occurrence of bifurcation of the vortex trajectories is explained as a resulting effect of three factors [14]: the nucleation rate, the Magnus force and the repulsion of vortices from each other. Starting from a certain value of the magnetic field, which depends on geometrical parameters of the tube, the potential energy is lowered by changing the vortex configuration, namely, by splitting a dense row into two sparse rows (Fig. 2c). Our results imply that superconductor open microtubes can be used as efficient vortex transport elements for fluxon-based information technologies.

Imaging of buried 3D magnetic rolled-up nanomembranes: Increasing performance and enabling novel functionalities of microelectronic devices, such as three-dimensional on-chip architectures in optics, electronics and magnetics, calls for new approaches in both fabrication and characterization. Up to now, 3D magnetic architectures had mainly been studied by integral means, e.g. ferromagnetic resonance [15], anisotropic magnetoresistance [16, 17], and cantilever magnetometry [18]. However, optimization of the performance of the magnetic 3D devices solely relies on precise tailoring of the local magnetic microstructures, which can barely be retrieved from integral
measurements. This goal can only be achieved by directly visualizing the magnetic domain patterns of the complex 3D object using magnetic imaging techniques relying on magneto-optical Kerr effect [19, 20] or soft x-ray [20, 21] microscopies. Very recently, we put forth the concept to visualize magnetization patterns in 3D magnetic objects based on an advanced analysis of the shadow contrast in X-ray magnetic circular dichroism photoemission electron microscopy (XMCD-PEEM) accompanied by the modeling of the XMCD contrast (Fig. 3) [21]. Although we exemplarily applied it to image buried magnetic spirals prepared using rolled-up nanotechnology, the approach can be generalized to magnetic objects of virtually any shape. We discriminated magnetic contributions from individual magnetic windings that provided means to derive the switching behavior and to reconstruct the magnetization in each layer of the magnetic spiral. Our concept can be extended to multi-component materials due to element sensitivity of the XMCD-PEEM as well as to heterostructures of arbitrary shape. By proper engineering the magnetic microstructures in these on-chip tubular architectures potentially allows to enhance their magnetoresistive as well as magnetoimpedance performance, which is relevant for prospective magnetoencephalography [22] and memory devices [23].

Direct transfer of magnetic sensor devices to elastomeric supports for stretchable electronics: Electronics of tomorrow will be flexible or even stretchable and will form a seamless link between soft, living beings and the digital world [24, 25]. The stretchability provides vast advantages over conventional rigid electronics particularly in consumer electronics and medical implants, where large area, extreme thinness and compliance to curved surfaces are the key requirements for the devices [26, 27]. Introducing stretchable magneto-sensorics into the family of stretchable electronics is envisioned to equip this novel electronic platform with magnetic functionalities [28-30]. Here, we introduced a novel fabrication platform for stretchable magneto-sensorics relying on a single step direct transfer printing of thin functional elements from a rigid donor substrate to a mechanically pre-stretched elastic membrane (Fig. 4) [31]. The method offers numerous advantages in terms of miniaturization and level of complexity and allows transferring an entire microsensor array including contact structures in a single step. Furthermore, relying on the new fabrication platform, we substantially enhanced the stretchability of transferred GMR multilayer up to about 30% relying solely on the wrinkled topology and the meander geometry, without the formation of cracks. The latter is of great importance as the sensor elements introduced here are truly strain invariant since without cracks almost no resistance change is associated with the tensile deformation.
Applications of the proposed technology platform are far-reaching: the presented direct transfer approach is not limited to magnetic nanomembranes, which renders possible the combination of magneto electronic components with other stretchable functional elements. In this way, smart multi-functional and interactive electronic systems can be envisioned for imperceptible [26] and transient [27] electronics where the magneto electronic components can add a sense of orientation, displacement and touchless interaction.


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Research topic 2.4

Nanoscale magnets


Responsible Directors: B. Büchner, L. Schultz, J. van den Brink

Summary: Nanoscale magnets range from single molecules to entities of a few million atoms. Due to their inherently small size and their large surface-to-volume ratio, the coupling of the magnetic cores to the local chemical environment significantly affects their magnetic moments and anisotropies. Understanding and controlling the properties of such nanomagnets at different length scales is thus at the heart of this research topic. The report reviews our work on nanoscale magnets in 2014. The materials related research on molecular magnets, magnetic nanoparticles and nanowires is complemented by efforts to develop novel methods and techniques which are particularly suited to characterizing magnetic materials at smallest possible length scales and with ultimate resolution.

Molecular magnetism

Nitride cluster fullerenes are endohedral fullerenes with triangular M₃N clusters (M = Sc, Y, or lanthanides) encapsulated inside the carbon cage. In these molecular structures different numbers of diamagnetic (DIA) and paramagnetic (PM) ions can be combined in one cluster which allows to separate single ion properties from the influence of interactions between lanthanide ions on the magnetic properties of such molecules. We have studied the magnetic properties of GdxSc₃−x N@C₈₀ (x = 1–3) as molecules with isotropic magnetic ions [1]. For x = 1 the magnetization follows a Brillouin curve pointing to a negligible single ion anisotropy. For x = 1 and x = 2, however, the magnetization curves reveal ferromagnetic (FM) interactions between the Gd³⁺ ions with coupling strengths of -1.2 K and -0.6 K for x = 2 and x = 3, respectively. DyxSc₃−x N@C₈₀ (x = 1–3), on the other hand, exhibits single molecule magnet (SMM) behaviour [2]. Here, the nitride ion in vicinity to the lanthanide results in a large single-ion anisotropy with a uniaxial ligand field and an alignment of the magnetic
moments along the lanthanide-nitrogen bond. As a result, DySc$_2$N@C$_{80}$ behaves as a single-ion magnet with butterfly-shape hysteresis below 5 K (cf. Fig. 1). For $x > 1$, exchange and dipolar interactions between the lanthanide ions strongly affect the SMM properties. While in Dy$_2$ScN@C$_{80}$, the FM coupling of Dy$^{3+}$ ions causes a broad hysteresis and large remanence, it leads to magnetic frustration and a narrow hysteresis in Dy$_3$N@C$_{80}$.

HoM$_2$N@C$_{80}$ and Ho$_2$MN@C$_{80}$ (with M = Sc, Lu, Y) were studied by NMR at room temperature [3]. Here, varying the radius of the DIA ions is found to cause a change of both the magnetic anisotropy of the Ho$^{3+}$ ions and the dynamics of the clusters in the fullerene cages. In HoSc$_2$N@C$_{80}$, also a single ion magnet behaviour was determined from AC-SQUID studies [4], albeit on a much faster time scale than in DySc$_2$N@C$_{80}$.

We have also synthesized the organonickel complex $[\text{NiBr(Mes)(phen)}]$ (1) (Mes = 2,4,6-trimethylphenyl, phen = 1,10-phenanthroline) and manipulated its magnetic properties electrochemically [5]. Electroreduction allows to switch it from DIA to PM. Surprisingly, in the reduced complex, the spin density is mainly located at a ligand molecule with a small leakage to the central metal ion rather than at the Ni-atom. Consequently, electroreduction forms a spin-radical center phen$^-$ bound to the central Ni atom, which has been monitored in-situ by ESR spectroscopy (cf. Fig. 2). The magnetic anisotropy is enhanced with respect to the free phen$^-$ radical due to the partially unquenched orbital momentum of Ni, which could be beneficial for possible applications.

**Magnetic Nanoparticles in Hard Disks**

Granular L$_{10}$-ordered FePt films in combination with heat-assisted magnetic recording (HAMR) are expected to soon replace CoCrPt perpendicular magnetic recording films (PMR) and to provide areal storage densities (ADs) beyond 1.3 Tb/in$^2$. To achieve this goal the uniaxial anisotropy of L$_{10}$-FePt (6.6 MJ/m$^3$) has to be fully developed in the grains and the [001] easy axes have to be aligned perpendicular to the film plane. Seed layers such as TiN, SrTiO$_3$ or MgO are needed to provide for this texture.
We have studied if and how Ar⁺ irradiation of the MgO seed layers helps to improve the FePt texture formation [6]. Structure and magnetic properties of the FePt-based media are characterized by X-ray diffraction (XRD), high-resolution transmission electron microscopy (HRTEM) and vibrating sample magnetometry (VSM). We observe a flattening of the MgO seed layer surfaces which goes along with a morphology change of the FePt grains from spherical to island-type shapes (cf. Fig. 3). This is attributed to the reduced number of nucleation sites for the FePt growth due to the smoothened seed layer surface. We also find an increased fraction of randomly oriented second layer particles and an enhanced coalescence of the FePt primary grains. These structural changes result in a reduced coercivity along the magnetic easy axis (out of plane) and an enhanced hard axis (in plane) remanence. Notwithstanding to the increased amount of coalescence, δm analysis of the magnetic interactions among the grains reveal weak dipolar couplings indicating that even the sintered grains switch as individual magnetic entities and that a treatment of the grain ensembles as Stoner-Wohlfarth systems is still permitted.

Magnetic Nanowires

One-dimensional, high aspect ratio nanoscaled magnets are prepared by electrodeposition within nanoporous templates. In recent years the focus was on iron based alloys with specific magnetic properties such as Fe₈₀Ga₂₀ showing high magnetostriction or Fe₇₀Pd₃₀ exhibiting a shape memory effect. Stable electrolytic baths have been achieved by complexing the metallic components and the deposition mechanisms were investigated in detail in order to identify key deposition conditions for the reproducible preparation of homogeneous, defect free nanowires [7, 8].

The as-deposited Fe₇₀Pd₃₀ alloy exhibits a nanocrystalline bcc phase structure but can be completely transformed to fcc as a starting point for MSM functionalization by high temperature heat treatment and subsequent quenching. Modifying the electrolyte by varying the Fe³⁺/SSC ratio (SSC: 5-sulfosalicylic acid, complexing agent) or addition of Cu²⁺ have been shown to cause a change of the structure from bcc to fcc already during deposition therefore avoiding any (unwanted) post-deposition annealing steps (cf. Fig. 4).

Quantitative MFM

We developed and implemented a new measurement concept of quantitative bidirectional force gradient microscopy [9] that can be directly applied to quantitative magnetic force microscopy. Quantitative force gradient measurements with cantilevers rely on the knowledge of the corresponding dynamic spring constants of the force sensor. We calculated such dynamic spring constants for two resonant oscillation modes, which correspond to two orthogonal oscillation directions of the probe tip, taking the specific geometrical structure of our novel sensors into account (cf. Fig. 5). We proved the
applicability of the quantitative bidirectional force gradient microscopy by showing a very good agreement between force gradient measurements based on magnetostatic interactions and corresponding calculations. Furthermore, our measurement principle relies solely on flexural vibrations. This is a strong practical advantage because all microscopy modes are based on vertical probe excitation and vertical deflection measurement only and can therefore be used with common dynamic scanning force microscopy setups.

**Magnetic dichroism with Electrons**

Similar to XMCD, electron vortex beams (EVBs), which carry quantized orbital angular momenta (OAM) L, allow to measure magnetic dichroism. Since electron beams can be easily focused to sub-nanometer diameters, this technique provides for unrivaled lateral resolution in magnetic measurements. In order to generate an EVB, specially designed apertures are needed. However, the dichroic signals to be measured with electron energy loss spectroscopy (EELS) are expected to be very small.

We have successfully implemented spiral- and fork-type apertures in the condenser lens system of our FEI Titan 80-300 transmission electron microscope (TEM) equipped with an image Cs corrector. This setup allows to generate EVBs with user-selectable OAM that can be used as probes in scanning TEM (STEM). While for spiral apertures, the different OAM are dispersed along the beam direction, for fork-type apertures, they are dispersed in planes perpendicular to the beam.

First investigations were focused on using spiral apertures, where the EVB is (de)focussed to select the OAM. We have shown that the diameters of $L = 0$ and $|L| = 1$ probes are 0.14 nm and 0.3 nm, respectively (cf. Fig. 6a/b). However, EELS did not provide any evidence for dichroism in several samples, and simulations have shown that with spiral apertures, the superposition of contributions from different OAM leads to an effective cancellation of L at the sample position [10].

We have, however, found that by using fork-type apertures in combination with an additional aperture in a modified condenser setup contributions from unwanted OAM can be effectively blocked. First experiments on FePt nanocubes reveal very encouraging results with dichroic signals in EELS from atom-sized EVB.

![Fig. 6: (a) Spiral type and (b) fork type vortex apertures to be inserted into the condenser system of a transmission electron microscope. (c) Electron vortex probes carrying orbital angular momenta of $L = -1$, $L = 0$ and $L = +1$ as generated by using a spiral type aperture. Probe diameters are roughly 0.14 nm and 0.3 nm for $L = 0$ (central spot) and $|L| = 1$, respectively.](image)


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Summary: Relying on the existing possibilities at the IFW to cover the complete range from developing a new material, its detailed characterization and its application in a specific device, we aim at a concerted research activity in the field of energy conversion/storage/efficiency. This activity includes development and characterization of materials for Li and Na batteries and capacitors as well as hydrogen production, storage and (re-)conversion to electricity for application on different length scales. In this report, we review our work in 2014, covering new insights into Li ion battery materials and their Li ion mobility, as well as hydrogen generation and storage applications.

Lithium dynamics in carbon-rich polymer-derived SiCN ceramics probed by nuclear magnetic resonance

The performance of a Li ion battery is determined, amongst other parameters, by the Li diffusivity of its electrodes. A versatile tool to study the microscopic jump process of the Li ions is nuclear magnetic resonance (NMR). By taking advantage of the available solid-state NMR techniques at the IFW, we have determined the Li diffusion parameters over a wide dynamic range in SiCN, a polymer-derived ceramic that possess novel physical, chemical, and mechanical features which can be tuned by subtle changes of composition and/or microstructure [1]. The slowest Li motion can be detected by linewidth (FWHM) and spin-spin relaxation ($T_2$) measurements of the $^7$Li nucleus. A change in the slope of the temperature dependent FWHM and $T_2^{-1}$ indicate a crossover from the motional narrowing (high temperature) to the rigid lattice regime (low temperature) which allows to determine the activation energy $E_A = 0.31$ eV of the ionic hopping process in SiCN. Further information about the faster Li motion on a timescale of $\mu$s can be obtained by measuring the spin lattice relaxation rate $T_1^{-1}$ in different magnetic fields and the rotating frame relaxation rate $T_{1\rho}^{-1}$. The temperature and frequency dependencies of the $^7$Li relaxation rates demonstrate that the Li dynamics in the polymer-derived SiCN ceramics is governed by a stable thermal activation law opening the possibility to fine-tune the Li diffusion parameters for specific battery performance.
Hollow silicon nanocomposites synthesized through economical chemistry as high performance anode in Li–ion batteries

Li–ion batteries are the first choice for many portable electronic devices owing to its high energy density and excellent rechargeability. Tougher requirements especially for mobile applications requires higher energy densities which can only be achieved by the development of high-capacity electrode materials [2]. Silicon is a promising candidate to replace graphite as commonly used anode with up to 10 times higher capacities owing to an alloying process of lithium with silicon. However, the large volume expansion of silicon during lithiation causes high stress inside the particles triggering crack propagation of individual particles causing a low cycle stability of silicon-based anodes [3]. We developed a stable silicon anode with a high capacity of up to 2000 mAh/g_{Si} (theoretical capacity of graphite = 372 mAh/g) which can be cycled for more than 1000 times with retaining 60% of its capacity [4,5]. We attribute the exceptional performance to ultra-small silicon nanoparticles (< 5 nm) which do not undergo crack propagation and, even more important, form a stabilized solid-electrolyte-interface owing to its high surface energy. Additionally, a well-designed carbon cage allows good interfacial electron transfer turning the composite into a high-performance anode material. We first form a precursor through simple polycondensation of high versatile and cheap trichlorosilane with water in the presence of a surfactant followed by a temperature treatment, carbonization and an etching procedure. Current research is ongoing to optimize the silicon anode for next generation Li–sulfur batteries and to investigate structural phenomena inside the silicon anode.

Nanomembranes for energy storage in lithium ion batteries at the macro-/microscale

Rolled-up nanotechnology offers an advanced strategy to deterministically rearrange two-dimensional nanomembranes into novel micro-/nanostructures for energy storage applications. Based on this technology and our previous works, we further demonstrate a hierarchical electrode design with just one material SiO_{x} for distinct functionalities by controlling the oxygen content x in each layer [6]. The resulted SiO_{x} (x = 1.85)/SiO_{y} (y = 0.5) bilayer nanomembranes as anodes exhibit a reversible capacity of about 1300 mAh/g at a current rate of 100 mA/g, an excellent stability of over 100 cycles, as well as a good rate capability (see Fig. 2(a)). Even after a deep cycling of 180 cycles at different current densities, the reversible capacity can recover completely to the original value at 100 mA/g. This excellent performance is due largely to the fast ionic transport, powerful strain accommodation and synergistic effect.
of oxygen-rich SiO$_x$ layer and silicon-rich SiO$_y$ layer. In order to perform a deep investigation of the electrochemical kinetics, an elegant lab-on-chip electrochemical device based on a single rolled-up Si tube is fabricated in our lab (see Fig. 2 (b)). Working as the anode in Li-ion batteries, the single tube exhibits enhanced diffusion in comparison to the planar film. After three charge/discharge cycles, the tube presents a wrinkled structure due to strain induced local deformation, which could be exploited to maintain a stable cycling and is consistent with the electrochemical performance of bulk electrodes [7]. This single tube device could be used as a promising ultra-microelectrode for other kinetic research, and an integrated full device could be developed as a local energy supply for powering ultra-compact microsystems.

Magnetic field-driven enhancement of hydrogen production in water electrolysis

The change in the German Energy Policy makes it necessary to develop novel methods for energy storage to buffer the differences between production and consumption. A highly promising way is the production of high-purity hydrogen via alkaline water electrolysis. Recently, it was shown that the efficiency of hydrogen production on planar electrodes was increased by the application of homogeneous magnetic fields normal to the electrode surface. This leads to a decrease of the bubble size and increase of the bubble release frequency and efficiency caused by magnetically induced electrolyte convections, so called magneto-hydrodynamic effect (MHD) [8]. To get a detailed understanding of the interaction of the electrolyte flow fields with the mechanism of bubble nucleation, growth and detachment, the hydrogen evolution on circular platinum microelectrodes under the influence of homogeneous and inhomogeneous magnetic field is studied at a specifically developed electrochemical setup. The process of bubble detachment is visualized with a CCD-camera and the velocity fields are analyzed by particle image velocimetry (PIV).

Simulations on in-situ HRTEM of nanosized MgH$_2$ at pressures of 1 bar H$_2$

Nanostructuring of hydrides has been shown to reveal improved thermodynamic and kinetic properties, which are strongly needed for application of solid-state hydrogen storage materials. However, most hydride phases such as MgH$_2$ cannot be studied at highest resolution by means of TEM, because of fast degradation upon irradiation with the imaging electron beam. This can be overcome using a novel nanoreactor (see Fig. 3 (a)) recently developed by H. Zandbergen (TU Delft). It allows for in-situ TEM studies at elevated hydrogen pressures (up to 4.5 bar) and temperatures (up to 500 °C). A point resolution of 1.8 Å has already been demonstrated experimentally for Cu nanocrystals.
We study the feasibility of HRTEM investigations of light weight metals such as Mg and its hydride phase with the nanoreactor by means of multi-slice HRTEM contrast simulations. Such a setup allows to fundamentally study the dehydrogenation and hydrogenation reactions at the nanoscale. We analyze the dependence of both spatial resolution and image contrast on parameters such as the defocus, metal/hydride thickness, hydrogen pressure and nanoreactor geometry to explore the possibilities and limitations of in-situ experiments with this reactor. Our simulations show that even for thicknesses down to 4.5 nm MgH₂, atomic resolution of the crystalline specimens can be obtained. Exemplarily, the simulated HRTEM image of a 12 nm thick MgH₂ nanocrystal in [110] orientation is shown in Fig. 3 (b). The atomic structure is clearly visible even in the presence of the top and bottom SiN window and an atmosphere of 1 bar H₂. The resolution is high enough to resolve neighboring Mg atom columns, which are separated by only 1.5 Å. Such simulations may be highly valuable to pre-evaluate future experiments and to design future nanoreactors.

Fig. 3: (a) Schematic illustration of the simulated supercell representing the nanoreactor. 20 nm thick electron transparent windows composed of amorphous SiN at the top and the bottom of the nanoreactor encapsulate the hydrogen gas. The MgH₂ nanocrystal is placed on the bottom window. (b) Simulated HRTEM image of a 12 nm thick MgH₂ nanocrystal in [110] orientation inside the nanoreactor. Blue circles represent Mg atoms and orange circles hydrogen atoms.

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Research Area 3 QUANTUM EFFECTS AT THE NANOSCALE

Research Topic 3.1 Designed interfaces and heterostructures


Responsible Directors: B. Büchner, L. Schultz, J. van den Brink

Summary: With the advent of advanced deposition techniques like pulsed laser deposition and molecular beam epitaxy it became possible to control the production of thin films and heterostructures on a level of atomic layers, thereby shifting genuine interface effects in the focus of scientific interest. Interfaces between certain complex oxides have attracted enormous attention due to the occurrence of unexpected phenomena, most notably the metallic conductivity between wide gap insulators [1]. Moreover superconductivity and magnetism have been observed [2, 3] and a variety of interface states with magnetic and orbital reconstructions not stable in the bulk materials [4, 5]. These findings raise both: the prospect of stabilizing even more exotic ground states at tailored interfaces and to exploit such effects in all-oxide devices. Beyond stabilizing interesting new states, a tuning of interface states is pursued by studying potential dependent phenomena at the metal/electrolyte interface [6]. This approach opens the way to electric field control of magnetism in metals at room temperature - exciting for potential use in multifunctional nanosystems and magnetic data storage.

In the following we will concentrate on three examples of ongoing research activities in the IFW concerning the interfaces between LaAlO₃ and SrTiO₃ and closely related materials, the properties of LaSrMnO₃ thin films on a NdGaO₃ substrate and the electric field control of magnetism at an electrode/electrolyte interface.

1. Polar heterointerfaces

The LaAlO₃/SrTiO₃ interface has been heavily studied during the last decade after the discovery of the insulator metal phase transition as a function of LaAlO₃ layer number. However, no consensus has been reached regarding the actual physical mechanism.
Research Area 3    QUANTUM EFFECTS AT THE NANOSCALE

triggering the phase transition. Although the so called “polar catastrophe” scenario, where the metallic state is a consequence of an electronic reconstruction alleviating growing internal electrostatic potentials in the overlayer, elegantly explains many experimental observations, it is steadily contested by scenarios involving point defects, such as oxygen vacancies. Our ansatz was to broaden the perspective by taking into account the isostructural and isovalent NdGaO$_3$/SrTiO$_3$ and LaGaO$_3$/SrTiO$_3$ systems, which all show an insulator-to-metal transition as a function of the overlayer thickness. The difference is the lattice mismatch between the SrTiO$_3$ substrate and the overlayer material, which is largest for LaAlO$_3$ and smallest for LaGaO$_3$. We investigated the electronic properties of NdGaO$_3$/SrTiO$_3$, LaGaO$_3$/SrTiO$_3$, and LaAlO$_3$/SrTiO$_3$ in a comparative study based on X-ray absorption spectroscopy, X-ray photoemission spectroscopy and resonant photoemission spectroscopy. Furthermore, LaV$_2$/SrTiO$_3$ interfaces were prepared for future investigations exhibiting a similar sharp insulator-metal phase transition at 6 monolayers.

First the nature of the charge carriers, their concentration and spatial distribution have been studied and quantitatively evaluated. The charge carriers are of Ti 3d character and the 2-dimensional sheet carrier density has a lower boundary in the range of 0.8 – 1.5 x 10$^{14}$ cm$^{-2}$ in reasonable agreement with Hall conductivity data. The extension of the charged near interface region must be at least 2 nm. Fig. 1 shows a compilation of the peak width of several core levels divided into substrate and overlayer excitations.

![Fig. 1: Full width half maximum (FWHM) of substrate and overlayer core levels.](image1)

![Fig. 2: Band diagram of polar heterostructures derived on the basis of photoemission data.](image2)
Clearly the overlayer lines have a tendency to decrease with layer number. This is not expected for the polar catastrophe model: the increasing electrostatic potentials would cause a line broadening. On the other hand a broadening is observed for the SrTiO₃ lines. From this and other measurements (exploiting the peak positions) a band diagram could be extracted (Fig. 2).

The behavior of the three analyzed heterostructures is found to be remarkably similar. The valence band edge of all the three overlayers aligns to that of bulk SrTiO₃. The conduction band offset differs due to the different gap values among the materials. The near-interface SrTiO₃ layer is affected, at increasing overlayer thickness, by the building-up of a confining potential. This potential bends downwards both the valence and the conduction band, the latter one crossing the Fermi energy in the proximity of the interface, and determines the formation of an interfacial band offset growing as a function of thickness. In this way a metallic interface region emerges. Quite remarkably, but in agreement with previous reports for LaAlO₃/SrTiO₃, no electric field is detected inside any of the polar overlayers. Especially the last point poses a serious obstacle for the polar catastrophe model in its original form. A possible way to circumvent this problem is the assumption that oxygen vacancies are created during the film growth and the subsequent charge transfer balances internal fields.

2. Manganate layers

For interfaces and thin layers the determination of important structural information such as interface terminations and stacking of atomic layers is often difficult. Here a scheme based on resonant x-ray reflectivity measurements is developed which is capable to provide such information with atomic resolution. Using LaSrMnO₄ as an example the theoretical and experimental implications of this approach are explored.

In simple words, the reflectivity is given by interference of x-rays that are reflected at the different interfaces realized in an artificial heterostructure. Referring to the reflection of optical light, an interface can be defined as a region in space where there is a change of the refractive index n. Similarly, also in the x-ray range even a small change in n will introduce an interface, thus a traveling x-ray wave will be reflected. This high interface sensitivity is what allows to accurately determine structural properties of heterostructures such as layer thicknesses and interface roughnesses by means of x-ray reflectivity. Going one step further at synchrotron light sources the reflectivity can be studied by tuning the x-ray photon energies to an absorption edge. At these so-called resonant energies, the refractive index depends very strongly on the valence shell configuration of the resonant scattering centers and, hence, the sensitivity to spatial variations of the electronic properties is dramatically enhanced at resonances.

By quantitatively modelling experimental reflectivity data of LaSrMnO₄ we obtained detailed information of the film structure as exemplified in Fig. 3. Resonant x-ray scattering will be a powerful tool for the investigation of a broad class of artificial heterostructures.

![Fig. 3: Structure of an LaSrMnO₄ film on an NdGaO₃ substrate.](image)
3. Electric field control of magnetism at the electrode/electrolyte interface

Electric field control of magnetism is a vision which drives intense research on magnetic semiconductors and multiferroics. Recently, also ultrathin metallic films were reported to show magnetoelectric effects at room temperature [6]. We study electric field induced changes of magnetism at the electrode/electrolyte interface. This approach allows to exploit potential dependent electrode processes as double layer charging, and/or faradaic reactions to control the surface magnetism. We achieved significant changes of anisotropy, coercivity and magnetization in FePt and CoPt. For Fe films, faradaic reactions involving Fe and iron oxide have been investigated and a reversible in- and decrease of saturation magnetization up to 64 % was achieved (Fig. 4). This opens the way to voltage controlled "on/off" nanomagnets. In a next step such a switchable surface Fe layer has been combined with a textured hard magnetic FePt layer. In this case, by exchange coupling through the interface, voltage control of the overall spin orientation has been achieved.

![Fig. 4: Voltage induced change of magnetization in Fe films probed by in situ Anomalous Hall Effect measurements.](image)


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Research topic 3.2

Self-organised electronic order at the nanoscale


Responsible Directors: B. Büchner, J. van den Brink

Summary: The objective of this research focus is to investigate self-organization phenomena in complex electron systems with pronounced electron-electron and electron-phonon interactions. The large families of transition metal oxides and transition metal dichalcogenides as well as the iron pnictides provide prime examples for materials, which realize such electron systems and which are also studied here. The present research effort takes great profit from the unique combination of complementary methods available at the IFW Dresden and as such merges state-of-the-art theoretical methods with leading-edge experiments. In this report, we focus on a specific highlight of our work in 2014, namely the relation between superconductivity and electronic order in real space as well as the emergence of complex orbital textures in transition metal dichalcogenides.

A great variety of interacting electron systems spontaneously form intrinsic electronic nanostructures, typically driven by strong electron-electron and electron-phonon interactions. The microscopic structure of such an electronic order is therefore a direct fingerprint of the relevant interactions in a system as well as the involved degrees of freedom. In addition to this, self-organized electronic orders are intensively discussed in relation to the most fascinating electronic phenomena we know today, like unconventional superconductivity, colossal magnetoresistance, strong magnetoelectric couplings or quantum criticality.

A strong motivation for the study of self-organized electronic orders is therefore to unravel the microscopic physics behind these phenomena. This is not only of great interest for basic research. It also bears relevance for applied science, since the
understanding of the microscopic mechanisms at work may also show up routes towards new technological applications. It is also very important to point out that recent advances in experiment and theory nowadays make it possible to probe, manipulate and analyze these electronic ordering phenomena in unprecedented detail. A famous case in point here are the magnetic skyrmions, which were first predicted by theory, then observed by momentum resolved experiments and, just in 2013, manipulated using spatially resolved scanning microscopes.

Notwithstanding these recent breakthroughs, we are only beginning to understand electronic order in complex materials and many important aspects still remain to be explored. Within this research topic we merge the unique expertise of the IFW in materials preparation (bulk, thin films, heterostructures and lateral nanostructures), experimental characterization (thermodynamics, scanning probes, x-ray spectroscopies, x-ray scattering, photoemission) and theoretical modeling (ab initio and model-based) into one coherent research effort. Central aim is to understand the coupling between electronic ordering in real space on the one hand and the electronic structure on the other hand. In this way, the present topic builds a bridge from fundamental research towards applications. The activities within this research focus are also part of the new Collaborative Research Center in Dresden (SFB 1143) and the Graduate School (GRK 1621) at the Technical University of Dresden.

During 2014, a number of complex electron systems displaying unconventional types of electronic order have been investigated, including iron pnictides [1], uranium-based heavy fermion compounds [2], bulk and nanostructures of transition metal oxides [3] and various transition metal dichalcogenides [4]. In this report, however, we will focus on new results regarding the electronic order in 1T-TaS$_2$ and 1T-TiSe$_2$, which illustrate how the strategy for this research focus has already put into practice.

1T-TaS$_2$ and 1T-TiSe$_2$ exhibit a number of charge density wave (CDW) phenomena that attract considerable attention, in particular because these electronic orderings occur in close proximity to superconductivity (SC). In fact, we found strong evidence that defects within the electronic superlattice formed by the CDW are essential to create superconductivity: Using high-pressure X-ray diffraction (XRD) experiments, we discovered a superconducting electronic crystal in 1T-TaS$_2$ that is characterized by a long-range order of solitonic defects within a CDW-superlattice.

**Fig. 1:** Pressure–temperature phase diagram of 1T-TiSe$_2$. **a)** Broad phase diagram showing CDW ordered, normal state and superconducting phase boundaries. The green color scale indicates the integrated intensity of CDW peaks, including both the C and IC components. The superconducting $T_C$ has been exaggerated by a factor of five for visibility. Points where the precise commensurability was measured are labelled C, I or C/I, indicating commensurate, incommensurate or coexistence, respectively. Ordered CDW-defects occur within the I-phase. **b)** Zoom-in on the region exhibiting the transition between commensurate and incommensurate order (grey dashed rectangle in **a**). From Ref. 5.
To better understand the connection between SC and such defects, we extended our investigations and used high-pressure XRD to directly study the CDW order in 1T-TiSe$_2$ [5], which was previously shown to exhibit SC when the CDW is suppressed by pressure or intercalation of Cu atoms. As shown by the phase diagram in Fig. 1, we succeeded in suppressing the CDW fully to zero temperature, establishing for the first time the existence of a quantum critical point at $P_c = 5.1 \pm 0.2$ GPa, which is more than 1 GPa beyond the end of the superconducting region. Unexpectedly, at $P = 3$ GPa we observed a reentrant, weakly first order, incommensurate phase, indicating the presence of a Lifshitz tricritical point somewhere above the superconducting dome. This study suggests that superconductivity in 1T-TiSe$_2$ is not connected to the quantum critical point itself. It rather further supports the notion that the formation of defects within the CDW order plays an important role for SC in the transition metal dichalcogenides.

In a very recent work, also done during 2014, we further found that CDW order in transition metal dichalcogenides does not only involve charge modulations. Instead we revealed a remarkable and surprising new feature of CDWs, namely their intimate relation to orbital order. Combining state-of-the-art density functional theory with leading-edge x-ray scattering and photoemission experiments, we not only showed that the CDW of 1T-TaS$_2$ within the two-dimensional TaS$_2$-layers involves previously unidentified orbital textures of great complexity. We also demonstrated that two metastable stackings of the orbitally ordered layers allow manipulating salient features of the electronic structure.

As can be seen in Fig. 2, for both metastable stackings a complex orbital texture within the ab-plane emerges. Note that not only the occupancy of a certain type of orbital changes spatially, but also the symmetry of the orbitals clearly changes from site to site, resulting in a complex orbital ordering pattern. For instance, whereas the orbital is oriented perpendicular to the ab-plane at the center of a Ta-cluster, a significant in-plane component exists at the cluster edges. It is also worth mentioning that the in-plane orientation of some orbitals changes as a function of the c-axis stacking and that also the S 3p-states take part in the orbital texture.

![Fig. 2: Real space illustration of the electron density for the highest occupied band of the CDW phase of 1T-TaS$_2$.](image)

(a), (b): A complex orbital texture emerges within the ab-plane. (c): The 1c-stacking allows for significant hopping only along the c-direction. (d): A substantial ab-component of the hopping appears for the 2a+c-stacking, which is metastable with the 1c stacking in (c).
The orbital stacking illustrated in Figs. 2(a,c) permits significant charge hopping only along c. In other words, the charges flow along orbital stripes along c, corresponding to the quasi one-dimensional character of the uppermost band close to the Fermi level. This drastically changes in the case of the stacking shown in Figs. 2(b,d). Now there is a significant ab-component of the hopping, so that the uppermost band attains a larger in-plane dispersion and crosses the Fermi level along Γ-M and Γ-K (not shown).

Based on these new insights from basic research, a new device concept has been developed, which we termed orbitronics. The orbital effects described above enable to switch the properties of 1T-TaS₂ nanostructures from metallic to semiconducting with technologically pertinent gaps of the order of 200 meV, as shown in Fig. 3 for a 1T-TaS₂ bilayer. This new type of orbitronics is a good example of how basic research can lead to new technological concepts, which is especially relevant for the ongoing development of novel, miniaturized and ultra-fast devices based on layered transition metal dichalcogenides.


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Summary: Next-generation photonic devices will rely on an ever increasing ability to route, trap, and otherwise manipulate light under tight tolerances. For example a precise control of the light emission wavelength is vital for the applications of single or entangled photons in quantum information sciences. Another example is the enhanced light-matter coupling in an optical resonator with tailored light trapping, which is central to a variety of exciting optoelectronic device concepts. In this context we have developed nanomembrane based technologies to manipulate light at micro- and nanoscales. Two photonic devices from our most recent progresses will be discussed in this review. The first is an on-demand and wavelength tunable single photon source, based on the light-hole emission from GaAs quantum dots embedded in a strain engineered membrane. The second is a microtube resonator fabricated with rolled-up titania nanomembranes, which has an optical resonance in the visible range.

Manipulation of light with nanomembrane technologies

Part I: Self-assembled quantum dot (QD) based SPs are one of the promising candidates for photonic quantum interface applications, with which the polarization state of single photons and the electron spin states can be coherently interconverted. By employing the large discrepancy between the g-factors of electrons and light holes (LHs) confined in a semiconductor QD, it is possible to realize bidirectional interconversion between the states of single stationary (spin) and flying qubits (photon).

We reported on-demand and wavelength-tunable LH single-photon emission from tensile-strained GaAs QDs embedded in nanomembranes [1]. The former property confirms the zero-dimensional character of our emitters, while the latter allows interfacing different QDs for remote entangling electron-spins. First we present the experimental methods of generating LH emissions from GaAs QDs. Then we demonstrate triggered LH
single-photon emission in the second-order time correlation measurements. We also show that the emission wavelength of LH single photons can be dynamically and precisely tuned in a wide range by means of an externally-induced strain field.

The sample studied in this work consists of GaAs/AlGaAs QD heterostructure embedded in two pre-stressed InAlGaAs layers, and was grown by solid-source molecular beam epitaxy (MBE). It includes a 140 nm-thick QD-containing nanomembrane on top of a 100 nm-thick Al0.75Ga0.25As sacrificial layer. In situ Ga droplet etching was used to grow GaAs QDs in AlxGa1-x As barriers (dot density < 10^8 cm^-2). In particular, the sample structure was designed in such a way that GaAs/AlxGa1-x As QDs layer is sandwiched between a pair of 20 nm-thick In0.2Al0.4Ga0.4 As stressor layers. After removal of the sacrificial layer in diluted HF solution, the compressed stressor layers expand inducing an in-plane (xy plane) biaxial tension of about 0.4% to the GaAs QDs. This feature results in the switching of the hole GS from a dominant HH character to a dominant LH character [1]. Thereafter, the free-standing QDs nanomembranes were transferred onto a 200 μm-thick piezoelectric crystal [Pb (Mg1/3Nb2/3)O3]0.72[PbTiO3]0.28 (PMN-PT) via Au-to-Au thermo-compressive bonding as illustrated in Fig. 1a. When an electric field Fp (//z) is applied to the PMN-PT, an in-plane biaxial stress field from the PMN-PT actuator is applied to the QDs nanomembranes. This allows for a precise tuning to the emission wavelength of single photons emitted by the LH-excitons, see the upper inset of Fig. 1b.

Of most interest is the pulsed optical operation of our device. This allows controlling the time of generation of excitons, and thereby realizing triggered LH single-photon emission. In order to achieve this, the diode laser is used to drive the QDs and meanwhile the second-order time correlation function is measured under pulsed excitation. The lower inset of Fig. 1b shows the unnormalized autocorrelation function of the in-plane polarized exciton emissions, and the quantum nature of LH single-photon emission is revealed by the significantly suppressed peak at zero-time delay. In addition, periodic peaks in the autocorrelation measurement are observed. This is an unambiguous signature of a triggered LH single-photon emission. The temporal distance between these peaks is found 12.5 ns, which is consistent with the excitation repetition rate of the diode laser, 80 MHz.

One of the most important elements for a LH-based reversible quantum interface is a ‘tuning knob’ for the ground state energy levels of different QDs, which facilitates the direct state transfer from the photon qubit emitted by one QD to the electron qubit in another QD. Such a tunability is demonstrated with our LH QDs in Fig. 1b.
electric field $F_p$ is applied to the PMN-PT actuator to generate an in-plane strain field on the QDs and a series of PL spectra from the QD are recorded as a function of $F_p$. Compared to the emission wavelength at $F_p = 0$ kV/cm, the LH single-photon emission can be blue-shifted (red-shifted) when a positive (negative) electric filed is applied. The total wavelength has been tuned by 3 nm (6 meV in energy) as $F_p$ is varied from -20 to 40 kV/cm. These results indicate that the optical properties of our LH single photon source can be accurately tuned, and stable single-photon emission during the tuning process is preserved.

**Part II:** Recently vertically rolled-up microcavities (VRUMs), as a novel form of whispering gallery mode (WGM) resonators, have attracted great interest and accordingly opened up several attractive applications thanks to advances in rolled-up nanotechnology. Key features of VRUMs include the capability of on-chip fabrication, the hollow core structure, and their ultrathin walls, which facilitate a highly penetrating evanescent wave sensitive to changes in the ambient refractive index. Depending on conditions, VRUMs can be structurally robust enough to be transferred onto foreign substrates. For these reasons, VRUMs are promising candidates for specialized tasks in integrated optics, optoelectronics, and lab-on-a-chip applications. Recently, we reported the inclusion of titania into the pallet of materials available for VRUMs.\(^3\) Titania, as a material, is an excellent candidate for optical devices due to its high refractive index while maintaining transparency through the visible. In combination with the fabrication strategies available using rolled-up nanotechnology, a wealth of optical structures with improved properties is possible. However, titania is still new to rolled-up nanotechnology and a considerable amount of effort has been required to optimize processes for this material.

We presented a systematic work on the fabrication and characterization of titania microtubes as an active material for different potential applications.\(^4\) We showed how titania microtubes can be rolled up using different sacrificial layers and discussed the possibility of controlling not only geometrical characteristics but also the physical properties such as the crystalline phase. The structural and optical properties of titania deposited under different deposition conditions were investigated on single titania membranes deposited on silicon substrates.

Titania microtubes can be successfully rolled up starting from different shapes and sizes of the pattern, for example square, circular and U-shape masks (Fig. 2). The square and
circular patterns usually result in a higher yield (close to 100%) as previously reported for SiO₂. On the other hand, the U-shape offers interesting opportunities in the design of optical resonators, since it avoids light leakage where the center of the tube is lifted from the substrate and facilitates axial confinement of light.

Optical characterization of resonant modes at telecom wavelengths was performed on U-shaped titania VRUMs by interfacing with a tapered fiber. Polarized light from a tunable IR laser was coupled into the fiber, and subsequently into the VRUM. Resonant modes are manifested by a sharp decrease in transmission through the fiber. By scanning the position of the fiber along the tube axis, controlling the angle that the fiber intersects the tube, and varying the polarization through the fiber, the coupling can be optimized. Figure 3 shows a representative transmission signal from a titania VRUM rolled-up from a U-shaped pattern following optimization of fiber coupling. Fiber coupling can be extended to create polarization-resolved mode maps that provide insight into the nature of light-matter interactions within rolled-up resonators. These experiments have been done in detail on HfO₂ coated silica tubes, leading to the observation of new optical modes as well opening the door to interesting utilizations.[5, 6]

The combination of titania with rolled-up nanotechnology presents many interesting opportunities for novel applications. Control over the structural and optical properties of rolled-up titania microtubes has been achieved by means of a proper tuning of the fabrication parameters. Optical characterization using tools such as polarization-resolved near-field maps of optical modes allow us to probe rolled-up resonators, providing feedback for fabrication improvements, leading to application.

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**Summary:** Recent studies of endohedral metallofullerene synthesis and electron transfer properties in IFW are reviewed. The first endohedral fullerene structure LaSc$_2$N@C$_{80}$ with heptagon is synthesized and characterized. High thermodynamic stability and low yield of LaSc$_2$N@C$_{80}$-$C_7$(hept) show that fullerene formation is not fully controlled by thermodynamic factors. New type of clusterfullerenes with two lanthanide ions, central carbon atom and Ti = C double bond (e.g. Lu$_2$TiC@C$_{80}$) is discovered and conditions for a highly selective synthesis of such species are revealed. A plethora of endohedral metallofullerenes with cluster-based redox activity and the mechanism of their redox reactions is described.

**Endohedral metallofullerenes: new cages, clusters, and electron transfer phenomena**

Endohedral metallofullerenes (EMFs) are hollow-shaped carbon cages encapsulating metal ions or cluster in their inner space [1]. By virtue of such hybrid structure, chemical and physical properties of EMFs are determined by (i) the fullerene cages, (ii) endohedral species, and (iii) by the phenomena resulting from the mutual interactions of the carbon cage and encapsulated cluster. All these aspects should be therefore carefully explored.

Various carbon cages have different π-system topology, which in due turn varies the frontier molecular orbital energies and their spatial distribution. Besides, geometrical properties of the σ-carcass (e.g. its size and shape) have crucial influence on their ability to form endohedral fullerenes [2]. Hence, the study of the possible fullerene cages and their role in EMF formation is an important aspect of the EMF research. According to the IUPAC definition, fullerenes are “Compounds composed solely of an even number of carbon atoms, which form a cage-like fused-ring polycyclic system with twelve five-membered rings and the rest six-membered rings”. The heptagon-containing fullerenes have been studied theoretically and were found less stable than conventional
pentagon/hexagon cages, and hence their formation in a standard arc-discharge synthesis has never been observed. The synthesis of nitride clusterfullerenes usually yields two isomers with the C_{80} cage that dominate in the M_{3}N@C_{2n} fullerene mixture [1]. The most abundant isomer has I_{h} cage symmetry, whereas the second most abundant structure is the isomer with the D_{5h} cage. However, our recent study of the mixed-metal La-Sc system revealed formation of the third isomer of LaSc_{2}N@C_{80}, whose structure was elucidated by single-crystal X-ray diffraction [3]. The new EMF structure has 13 pentagon and is the first example of an EMF molecule with a heptagonal ring (Fig. 1). Computational DFT study shows that LaSc_{2}N@C_{80} with heptagonal ring is almost as stable as the I_{h} cage isomer, which refute the claims on the low stability of heptagon-containing fullerenes. If the isomeric distribution would be governed by the thermodynamic stability, a much higher yield of the heptagon-containing isomer might be expected. However, experimental studies contradict this expectation. The reason for the low yield of heptagonal fullerenes may be in the kinetic factors, i.e. the ease of the structural rearrangement to other fullerene cages. Comparison of the C_{80}-C_{7}(hept) and the most abundant C_{80}-I_{h} cage isomers reveals their close similarity. These two structures are related by a single Stone-Wales transformation, i.e. a “rotation” of the C_{2} fragment highlighted in light green in Fig. 1 by 90° and corresponding readjustment of the σ-cage network. The barrier towards such rearrangement of ca 6.5 eV is rather high for a room temperature but can be easily accessible in the hot carbon arc during the fullerene formation.

The mutual stabilization of the cage and endohedral species is well understood based on the metal-to-cage electron transfer, but prediction of the structures of possible endohedral cluster remains a challenging problem. A plethora of metal or hybrid metal/nonmetal clusters has been already encapsulated within the carbon cage, and new examples of species capable of forming the EMFs molecules are continuously reported. Choosing the type of clusterfullerene to be formed and a metal or a combination of metals to be encapsulated the electronic and magnetic properties of EMFs can be varied in a broad range. Hence, exploration of the species which can be encapsulated into the carbon cage during the EMF formation is another important aspect of the EMF research, where serendipity plays an important role. In an attempt to synthesize of the mixed-metal Ti-Lu nitride clusterfullerenes by the arc-discharge with NH_{3} reactive gas atmosphere our group recently discovered formation of the new type of clusterfullerenes, in which the central atom is carbon making a double bond to a titanium atom and single bonds to two lanthanide ions (Fig. 2) [4]. In fact, the structure of Lu_{2}TiC@C_{80} is very similar to that of Lu_{2}ScN@C_{80}, to which it is isoelectronic. Further exploration of reaction conditions revealed that Ti-carbide clusterfullerenes can be obtained with high selectivity by introducing methane CH_{4} into the arc-discharge generator.
Irrespective of the endohedral cluster composition, all EMFs have one common element – the metal/π-system interface. Behaviour of this interface under electron transfer conditions has been thoroughly studied by electrochemistry and spectroelectrochemistry. While the carbon cage is the only redox-active center in empty fullerene, in EMFs both the fullerene cage and the endohedral species can be redox active. Of particular interest are EMFs exhibiting endohedral redox activity. In such processes, the fullerene cage merely acts as an inert container, transparent to electrons and stabilizing the variable spin and charge state of endohedral species [5]. Lu₂TiC@C₈₀ is an illustrative example of such EMF: its LUMO is to a large extent localized on Ti ion, and reduction of Lu₂TiC@C₈₀ proceeds via the change of the Ti valence state. On the contrary, reduction of isosctructural and isoelectronic Lu₂ScN@C₈₀ is a cage-based process and is shifted to a more negative potential range by 0.51 V [4].

Unique redox behaviour of endohedral Ce³⁺ ion is found in cerium-based nitride cluster-fullerenes such as Ce₇N@C₈₀ (M = Sc, Y, Lu) [6]. Due to the large ionic radius of Ce³⁺ (1.01 Å), encapsulation of Ce-based nitride clusters within medium-size carbon cages results in the significant inner strain. Oxidation of Ce³⁺ via removal of the 4f electron forms Ce⁴⁺ with much smaller ionic radius (0.87 Å), and therefore strained Ce-based EMFs are prone to oxidation as a way to release the strain. The Ce-based oxidation of such EMFs can be proved by NMR spectroscopy as exemplified in Fig. 3 for CeSc₂N@C₈₀: formation of the diamagnetic [Ce⁴⁺Sc₂N@C₈₀]⁺ cation results in the shift of ¹³C and ⁴⁵Sc NMR resonance lines in comparison to the paramagnetic Ce³⁺Sc₂N@C₈₀. Variation of the Ce₇N cluster by choosing the metal M of different size (Sc, Lu, Y) modifies the inner strain and therefore changes oxidation potential of the endohedral Ce⁴⁺/Ce³⁺ pair. On the other hand, variation of the carbon cage also results in the changes of the inner strain. A systematic study of Ce₇M₃−N@C₉₈ with different cage size (2n = 78–88) showed that the oxidation mechanism of these molecules is governed by a subtle balance between the cluster and the cage size [7].

**Fig. 3:** Top: ¹³C and ⁴⁵Sc NMR spectra of CeSc₂N@C₈₀ and [CeSc₂N@C₈₀]⁺. Bottom: change of the cluster shape in Ce₇N@C₈₀ from highly strained pyramidal to planar induced by oxidation.
Sc₃N@C₈₀ is an example of endohedral redox activity with Sc₃N-based reduction. Chemical derivatization such as cycloaddition changes the π-system of the fullerene and hence can substantially affect the electrochemical properties of Sc₃N@C₈₀. Sc₃N@C₈₀ has two types of CC bonds located at pentagon/hexagon [5,6]) and hexagon/hexagon [6,6] edges. The anion radicals of isomeric [5,6] and [6,6] Sc₃N@C₈₀ benzoadducts were studied by electron spin resonance spectroscopy [8]. In both compounds the rotation of the Sc₃N cluster is frozen and the spin density distribution of the cluster is highly anisotropic, with hyperfine coupling constants of 9.1 and 2 × 33.3 G for the [5,6] adduct and −0.6 and 2 × 47.9 G for the [6,6] adduct. Remarkably, the subtle variation of the exohedral group position on the surface of the cage results in very pronounced changes of the spin density distribution and on the dynamics of the encapsulated Sc₃N cluster.

![Molecular structures, spin density distribution, and ESR spectra of anion radicals of isomeric [5,6] and [6,6] Sc₃N@C₈₀ benzoadducts.](image)

**Fig. 4:** Molecular structures, spin density distribution, and ESR spectra of anion radicals of isomeric [5,6] and [6,6] Sc₃N@C₈₀ benzoadducts.


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Research Area 4    TOWARDS PRODUCTS

Research topic 4.1

**Surface acoustic waves: Concepts, materials & applications**


**Responsible Directors:** B. Büchner, J. Eckert, O. G. Schmidt

**Summary:** The center “SAWLab Saxony” was established bringing together IFW’s competence in acoustoelectronics with those of other Saxon research groups and high-tech companies active in this field. In 2014 the research emphasis was mainly put on the thorough investigation of high temperature durable piezoelectric substrates and appropriate electrode metallization systems for SAW devices as well as on systems with acoustofluidic interaction. Hereby, different new piezoelectric materials were characterized regarding their acoustic behavior and a complete parameter set was established for CTGS crystals as currently the most promising member of langasite family for high temperature applications. As for advanced thin film electrodes systems made of refractory elements, AlRu alloys and metallic glasses were investigated. Moreover dedicated analysis methods were developed for surface- and interface studies on SAW-based film systems.

In the research topic 4.1 the „SAWLab Saxony - Competence Center for Acoustoelectronic Fundamentals, Technologies and Devices“ (www.SAWLab-saxony.de) was founded, joining all microacoustic activities of the IFW Dresden and combining this expertise with competences and skills of cooperating Saxon research institutes, universities and high-tech companies. This interdisciplinary research includes acoustoelectronic fundamentals and novel materials as well as advanced applications with exploitation by innovation-oriented small and medium-sized enterprises. In this frame, IFW activities will continue to focus on emerging and future-oriented fields of SAW components, like high-grade frequency filters and resonators as well as sensors and actuators with enhanced capabilities. Here, materials aspects are crucial regarding piezoelectric substrates and thin film electrodes with increased temperature and power capabilities necessary for
SAW structures with enhanced precision and lifetime. Besides fundamental investigations regarding general effects of wave propagation [1], dynamic behavior of polar dielectrics [2] and acoustofluidic interaction phenomena, the research was also focused on dedicated materials for high-temperature applications such as i) advanced piezoelectric substrate materials, ii) new routes for thin film electrode materials with high thermal stability and iii) dedicated surface and interface study.

i) Advanced piezoelectric substrate materials
Besides commercially well-established high frequency filters, resonators and actuators, SAW devices presently capture new fields of application namely as passive SAW-based sensors and ID tags. Due to inherent robustness and the capability for wireless interrogation such devices become ready for an emerging field of industrial and consumer applications. Nevertheless, a remaining challenge is still the required durability against extreme temperatures, particularly in oxidizing atmosphere. Here, new piezoelectric crystals were characterized with high precision regarding their acoustical material parameters, among them different members of langasite and oxoborate families. A serious alternative for high temperature SAW devices is CTGS (Ca₃Ta₅Ga₃Si₂O₁₄) belonging to the same crystal family like the commonly used LGS (langasite, La₃Ga₅SiO₁₄) but showing a more ordered and thus more stable crystal structure. By combining different techniques based on SAW and BAW (Pulse-Echo, Resonance-Antiresonance, LAwave) with dielectric measurements a strongly improved complete set of acoustic material data was determined for room temperature, overcoming the inaccuracies of formerly known data sets.

ii) Thin film electrode material systems with high thermal stability
High-temperature stable electrode systems based on magnetron sputtered refractory metals like tungsten and molybdenum single and multilayers as well as intermetallic Al(Ru) thin films were investigated on LGS and CTGS substrates. The choice of these material systems is based on their high melting point (> 2000 °C) and thus a minimal creep related damage as well as a compliant coefficient of thermal expansion (CTE) of the materials in contact to the substrates. Additional features are a relatively high thermal conductivity and low electrical resistivity (< 15 μΩcm for 100 nm thin films) which is stable over many temperature cycles. In-depth material characterization was performed to understand and tailor the microstructure using different techniques such as X-ray diffraction and reflectivity measurements, scanning and transmission electron microscopy, Auger electron spectroscopy, atomic force microscopy etc.

Since even at high temperatures a chemical reaction with the substrate was not observed for W/Mo a diffusion barrier to the CTGS substrate is not necessary. A high thermal stability up to 800 °C of all the W/Mo films on CTGS was also observed under vacuum (Figs. 1,2). The RuAl alloy thin films (thickness 110 nm) have also been heated up to

![Fig. 1: Focused ion beam cuts of W/Mo multilayers on CTGS after annealing at 800°C for 12h (a - d: increasing number of layers).](image-url)
For this material system the phase formation, surface morphology, electrical conductivity and film architecture have been investigated. The results show that the RuAl phase is formed very well on reference Si/SiO₂ substrates but oxidation of the Al atoms takes place due to diffusion of O out of LGS and CTGS substrates. This oxidation effect destroys the RuAl phase completely at 800 °C on LGS substrates (Fig. 3). This behavior is less pronounced on CTGS. However, the results on Si/SiO₂ reference substrates prove that the RuAl alloy is also a promising metallization candidate for SAW devices, but one needs to overcome the challenges on LGS and CTGS by appropriate barrier layers to inhibit the diffusion of O and to protect the film against oxidation. In conclusion, the W-Mo and Al-Ru materials systems are suitable metallization candidates for high temperature SAW devices, being an alternative to the commercially used Pt thin films electrodes [3].

Thin film metallic glasses are characterized by a high yield strength and a low diffusivity at moderate resistivity compared to crystalline thin films of the same dimensions. Due to the lack of microstructural defects such as grain boundaries (Fig. 4), internal diffusion and degradation effects are drastically reduced. The research has been focused on...
fundamental investigations especially on the binary Ni-Zr as well as Cu-Ti material systems for SAW device applications. For this purpose the alloys were deposited by simultaneous co-sputtering whereas for multilayers the two material components were deposited successively. On both material systems the surface roughness, intrinsic mechanical stress, electrical resistivity, crystal phase formation as well as the Young’s modulus were studied in dependence on composition. It was observed that microstructure and phases have a strong influence on the measured properties. In particular an extremely low surface roughness in the nm range and electrical resistivity below 200 μΩcm are results observed for the amorphous thin films [4].

The interface between the metallization layer and the piezoelectric substrate is crucial regarding the texture of the layers and their microstructure evolution, and thus influences performance and lifetime of SAW devices especially under high acoustic load. Studies on LiNbO3 and LiTaO3 with several metallization layers (Ta, Ti, TaNx, TiNx) emphasize the role of cleaning pre-treatment of the substrate surface on layer performance. Conventional preparation like low energy ion etching or thermal treatment may alter the chemical state of the surface. Based on analytical results using a dedicated Angle-Resolved X-Ray Photoelectron Spectroscopy (ARXPS) algorithm an rf-plasma treatment process was developed that results in an ideal cleaned surface. This ARXPS algorithm allows a complex interface modelling with robust mathematical approach that can lead to further understanding of the interface effects [5].

Fig. 4: FIB cross sections of a crystalline Ni and an amorphous NiZr thin film.


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Research Topic 4.2

Materials for biomedical applications


Responsible Directors: B. Büchner, O. G. Schmidt, J. Eckert

Summary: Advances in biomedical applications require novel material-based solutions under exploitation of their unique properties. The combination of different material classes yields biofunctionalities at greater dimension in analytics, diagnostics and therapeutics. A profound knowledge-base on the interaction of the material with the biological system has to be developed to tailor materials properties and to control the bio-solid-interface. At the IFW a unique expertise on different material classes for novel biomedical applications is concentrated ranging from nanomaterials (carbon nanostructures, rolled-up materials) over bio-microfluidics and microacoustics based on thin films up to bulk materials. A special research focus are new Ti-based alloys for hard tissue regeneration and replacement with most suitable mechanical performance and excellent biocompatibility. A key aspect is the design of bioactive surface states for optimum bone–metal interactions towards reliable osseointegration also in case of age-induced bone diseases. Successful examples of nanoscale surface modifications of a new generation of Ti-based implant alloys are demonstrated in the following.

Nanoscale surface modification of Ti-based alloys for hard tissue implants

A world-wide growing population of elder people and the related rising problem of age-induced bone diseases like osteoporosis tighten the demands on materials properties used for human orthopaedic implants towards better mechanical and biological compatibility and longevity. For hard tissue regeneration, Ti and its alloys are the most favoured implant materials, but there are still serious problems to be solved. A major issue is the bone-implant stiffness mismatch causing stress-shielding effects with consequence of bone resorption and implant loosening. Multiple cases of implant failure due to limited materials strength are observed. The release of toxic metallic species by corrosion and
wear is problematic due to inflammatory cascades. Suitable surface states must be created which enable better osseointegration. Therefore, careful material design is necessary to attain optimum biofunctionalities [1].

We develop new non-toxic Ti-based materials with suitable balance of low stiffness and high static and dynamic strength as well as high durability under physiological conditions. This comprises alloy design with particular microstructural features at different length-scales ranging from microcrystalline via nanocrystalline to amorphous states. In the focus are alloys of the metastable Ti-Nb system. For beta-type Ti-(40-45)Nb, compositional modifications with beta stabilizers like indium or grain refiners like boron and variations of casting and thermo-mechanical processing conditions are studied to suitably tailor microstructure-property relations [2]. Porous alloy structures with very low elastic modulus are produced via powder metallurgical approaches and are intended to be used as mechanically stable substrates and carrier of bioreabsorbable materials or drug delivery systems in bone defects [3]. Special emphasis is given to alloys that mechanically stimulate bone healing processes based on a combination of superelastic and shape memory effects like martensitic Ti-(13-30)Nb [4]. Amorphous Ni- and Cu-free Ti-based alloys are a particular class of materials that are developed towards an optimum balance between maximum glass-forming ability and outstanding mechanical performance and corrosion resistance [5,6].

A decisive prerequisite for long-term implant application of those novel Ti-based alloys is the generation of bioactive surface states for optimum osseointegration. That comprises the control of the complex processes at the bio-solid interface towards the stimulation of the activity of bone forming cells (osteoclasts) against that of bone resorbing cells which is the basis for bone tissue regeneration. The implant surface state with its topography and roughness, composition and surface energy controls these interactions. Many established surface treatments for commercial Ti-based implant materials yield distinct micrometer-sized features. But recent studies revealed that nanometer-sized modifications better scale with cell functions. Therefore, strategies for the generation of suitable nanoscale surface modifications of the new generation of Ti-based implant materials are to be developed. Selected successful examples for beta-type Ti-Nb alloys are discussed in the following.

The high Nb content of Ti-(40-45)Nb alloys yields an extremely high corrosion resistance and therefore, established acid etching procedures for metallic implant materials are not sufficient for effective surface modification. In a new approach the applicability of a H2SO4/H2O2 treatment for chemical nanoroughening of the alloy surface was demonstrated [7,8]. The nanotopography comprises a network of nearly semi-spherical pits of 25 nm mean diameter (Fig. 1). While the native passive layer on a mechanically ground alloy surface is very thin and has a mixed state of various Ti and Nb-oxides, the chemical treatment enhances the passive layer growth. A strong enrichment of Nb2O5 relative to TiO2 in the surface layer was detected. The use of analytical methods such as X-ray photoelectron spectroscopy (XPS) (Fig. 2) and Auger electron spectroscopy (AES) is

![SEM micrograph of a Ti-40Nb surface after chemical nanoroughening](image-url)
crucial for the characterization of the materials chemical surface states. But it is challenging due to limited lateral resolution, chemical effects on peak shifts and shapes and the destructive nature of depth-profiling with ion sputtering. Tailored approaches were implemented to allow the calculation of (semi-)quantitative element concentrations from depth profiles [9]. In vitro analyses were conducted at the TU Dresden (AG Hempel) and clearly indicated that chemically nanoroughened Ti-Nb surfaces increase the metabolic activity and osteogenic differentiation of human mesenchymal stromal cells (hMSC) (Fig. 3). Those effects are significantly more pronounced for the alloy than for cp-Ti.

When an implant surface is in contact with a physiological environment, one of the first processes is the formation of an extracellular matrix as basis for bone cell adhesion, spreading and differentiation finally leading to bone tissue growth. A recently emerged idea is to stimulate those cell reactions by mimicking an extracellular environment with synthetic means. This comprises the creation of well-defined ordered nano-topographies on bulk solid surfaces in terms of nanoparticle patterns and their functionalization with bioactive molecules. Our collaboration partner at Univ. Heidelberg (AG E.A. Cavalcanti-Adam) developed an approach that starts with nanolithography based on dip...
coating of Au-loaded diblock copolymer micelles for monolayer formation on a solid
substrate and subsequent oxygen plasma treatment for removal of the organic residues.
In our joint study we could demonstrate that by this way highly ordered hexagonal
patterns of Au nanoparticles with 5-7 nm diameter and interparticle distances ranging
from 70 to 100 nm (depending on the polymer-type used) can be created on fine-polished
beta-type Ti-40 Nb surfaces. The near-surface regions were characterized with TEM, this
way the detailed nature of the fcc Au nanoparticles was analysed and an amorphous
passive layer of (Ti,Nb)-oxides which was formed during the plasma treatment was
detected (Fig. 4). Samples with those surface states were coated with polyethylene
glycol and the Au nanoparticles were functionalized with cyclic thiol-peptide ligands. In
vitro tests revealed significant effects on the early response of hMSC towards an improved
regulation of local cell adhesion and a reduction of the population heterogeneity. Those
biofunctionalized nanopatterned alloy surfaces appear to be very promising tools for
selecting hMSC with homogeneous phenotype [10].

Fig. 4: TEM image surveying the near-surface regions of Ti-40Nb with passive layer and
arrangement of Au nanoparticles


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³University of Ioannina, Greece
Summary: The increasing demand of industry for equipment (tools, devices, machine parts, accessories etc.) with excellent durability under extreme loading conditions promotes the development of innovative materials possessing e.g. high strength, hardness, wear resistance, ductility and corrosion resistance. Novel manufacturing technologies, such as special casting methods, which ensure accelerated solidification, selective laser melting and thermoplastic forming present a fast and energy efficient option for load-adapted adjusting of mechanical properties. Materials under investigations are metallic glasses, glass-matrix composites, crystalline materials with extraordinary mechanical properties, as e.g. high strength steels, high strength lightweight alloys, highly strengthened conductors, and cement-based materials reinforced with carbon nanotubes. The basic idea is to transfer sophisticated technologies combined with specific newly developed materials towards industry.

High performance steel alloys

This topic contains a multiplicity of activities and projects, respective (1) high strength and/or corrosion resistant tool steels, (2) parts of high strength steels produced by selective laser melting (SLM) and (3) filler material (steel wire) in overlay welding processes. By applying a tailored casting, SLM or welding process and sufficiently high cooling rates excellent mechanical properties (compression strength of up to 5.5 GPa combined with a plastic strain of 20%) can be obtained for the steel alloys already in
Research Area 4    TOWARDS PRODUCTS

as-prepared state [1]. This opened the possibility for reducing multi-stage, time-con-
suming and cost-intensive manufacturing processes and led to several patents [2-6].
Since no subsequent heat-treatment is required, the cooling parameters applied during
the casting process play a key role with respect to the evolving microstructure and
resulting properties. Therefore, detailed investigations of the phase formation, especial-
ly the crystal structure and morphology of numerous types of carbides were performed
(Fig. 1a, b) [7] and accompanied by thermodynamic modelling work. This resulted in a
profound understanding of possible ways for tuning the microstructure and properties
of these alloys to certain application purposes, e.g. for cutting/punching/mining tools
(Fig. 2a - c) with excellent service life as well as filler material (wire) for deposition
welding [6]. Furthermore, reinforcing lattice structures were prepared by SLM for
various applications (Fig. 3).

**High strength metallic materials prepared by SLM**

It could be demonstrated for the first time that bulk metallic glasses are producible by
selective laser melting. The method opens a possibility to overcome intrinsic limitations
regarding the complexity and dimensions of the obtainable geometries compared to the
commonly known casting process. For the first successful experiments an iron-based
metallic glass was used, but this approach is viable for a variety of metallic alloys [8].
Furthermore, there is a strong demand from aerospace industry for the develop-
ment of high strength and lightweight materials with enhanced properties. The SLM
process enables the manufacturing of precise and homogenous multicomponent Ti- and
Al-based alloys nearly without limits in design and ensures the research on sophisti-
cated alloys with very different physical and chemical characteristics [9,10].

**Thermoplastic forming of bulk metallic glasses**

The unique crystallisation behaviour of metallic glasses enables a thermoplastic form-
ing process in the supercooled liquid region (SCLR), because of the significant soften-
ing of the BMGs above $T_g$. These special characteristics lead to processing temperatures
and pressures that are similar to those of plastics. The main advantage is the decoupling
of the rapid cooling, required to form the amorphous structure, from the shaping
process. In close collaboration with the research technology division of IFW a device has
been developed that allows producing semi-finished products of refractory metal-based
glassy granulates in protective atmosphere. First parts using such Zr-based glass gran-
ulate have been prepared by shaping the glass above the glass transition temperature
just in order to demonstrate the feasibility of the technology.

**Stress and fatigue corrosion of bulk metallic glasses**

Stress corrosion cracking investigations are carried out on the bulk glassy
Zr$_{52.5}$Cu$_{35.5}$Al$_{10}$Ni$_{4.5}$Ti$_{3}$ alloy (Vit 105) by means of three-point bending at constant
deformation in chloride-containing electrolytes with an in-house designed setup. A
special three-electrode electrochemical cell is placed around the test sample and en-
ables in situ polarisation control and measurement. Potentiostatic experiments during
static mechanical loading are performed at several anodic potentials and chloride

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**Fig. 1:** (a) Optical micrograph of the dendritic structure of the as-cast Fe$_{84.3}$Cr$_{4.3}$Mo$_{4.6}$V$_{2.2}$C$_{4.6}$ alloy showing the distribution of the present phases; (b) SEM image of the deep etched Fe$_{84.3}$Cr$_{4.3}$Mo$_{4.6}$V$_{2.2}$C$_{4.6}$ alloy illustrating the fine network-like structure formed by complex carbides and its arrangement within the material.

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**Fig. 2:** (a) Knives for medical filter production; (b) bucket tooth; (c) pick head for mining machine.

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**Fig. 3:** Lattice structure produced by SLM technology.
concentrations selected based on anodic polarisation experiments [11]. Typically, under static loading, after a certain incubation time, the current starts to increase suggesting the initiation of localized corrosion. At a later point, the stress also starts to decrease gradually indicating stress corrosion cracking with stable crack propagation. At the end, unstable crack propagation is observed, which is due to overload of the remaining load-bearing section. Microscopic analysis of fracture surface revealed a clear distinction between the two modes of crack propagation. Stress corrosion cracking is perpendicular to the major tensile stress component. This is accompanied by crack branching and very limited shear banding (Fig. 4).

**Functionalized carbon nanotubes in cement-based composites**

The use of the reinforcing effect of carbon nanotubes on the tensile strength of cement-based composites requires a strong CNT-matrix interaction which would promote load transfer across the interface. In order to understand and predict the phenomena taking place at the CNT-matrix interface, various types of carbon nanotubes prepared using acetonitrile, cyclohexane, and methane as the carbon source were examined with regard to their surface properties. Working in close collaboration with Leibniz Institute of Polymer Research, significant differences were revealed in the acid-base features, surface tension as well as in the wetting behavior of the prepared CNTs. For example, the hydrophobicity of the CNTs decreases by utilizing the carbon sources in the following order: cyclohexane, methane, and finally acetonitrile. The sol-gel coating of the CNTs with silica showed strong dependence on the chemical composition of the nanotube surface [13]. This basic research is a prerequisite for the specific application of CNTs in inorganic cementitious materials.

**High-strength Cu-based conductor materials**

The microstructure of single phase copper alloys is altered by cold deformation. Depending on the processing parameters like temperature and intrinsic material parameters as stacking fault energy, the dominant deformation mechanism is different and the refinement of the microstructure bears other rates with respect to the deformation strain. The formation of deformation twins is activated at low homologous temperature or at low stacking fault energy. Both also lead to smaller grain sizes achieved at a certain deformation strain. Lowering the temperature only yields to a high efficiency in strain hardening with respect to room temperature deformation for intermediate stacking fault energies. The maximum efficiency occurs in the vicinity of the onset of deformation twinning at room temperature which was found for a stacking fault energy of 30 mJ/m². In this condition cryo-deformed CuAl3 alloys show a strength of 890 MPa, which represents an enhancement of 180 MPa when compared to room temperature deformation [14]. Further research will foster this conception of activating mechanical twins by cryo-deformation also in CuAg alloys which so far showed the optimum combination of high strength and high electrical conductivity.

**Brazing material corresponding to particular industrial requirements**

Many components used in structural and functional applications are permanently joined by brazing. Therefore, a multitude of different and complex braze fillers are on the market to fulfill the specific requirements defined by each combination of materials. The melting range of the braze filler has to match the target temperature and the process-ability of the alloy has to be adequate in order to ensure large-scale production. In addition, next to a sufficient wettability also the interactions and reactions at the solid-liquid interface are crucial for understanding and improving the brazing process. In cooperation with Umicore AG & Co. KG a substitute alloy for the industrial standard braze filler AgCu28 has been successfully developed and systematically investigated (Fig. 5).
Due to an extensive alloy development combining materials science and industrial demands a composition based on the ternary system Cu-Ag-Ga has been characterized and patented. The new braze filler contains 40% less Ag. The effect of the additional element Ga on the wettability on stainless steel surfaces was investigated on the macroscopic scale (contact angle measurements) as well as on the microscopic scale (SEM, TEM), so that a detailed understanding of the complex brazing process was achieved.

**Electrochemical micromachining of metallic glasses**

Owing to their outstanding properties bulk metallic glasses are very promising materials for the production of microparts. But shaping them without heat input is still a challenge. An alternative microprocessing method, which operates at room temperature, is the pulsed electrochemical micromachining (ECMM). Employing ultra-short voltage pulses between a micro-sized tool electrode and the BMG surface induces a highly localized material removal process. The applicability was firstly proven for Zr- and Fe-based BMGs using non-aqueous electrolytes. But due to its inmanent risks the employment of methanolic solutions is not favorable. However, using aqueous solutions Fe-based BMGs form stable passive layers, which disturb the machining. These effects can be minimized by adding an oxidizing agent Fe$_2$(SO$_4$)$_3$ [12]. To demonstrate the high potential of the ECMM optimum hole and line structures were machined (Fig. 6).

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Fig. 6: Optical micrograph of the surface of a bulk glassy Fe$_{65.5}$Cr$_{14.7}$Mo$_{4}$Ga$_{4}$P$_{12}$C$_{5}$B$_{5.5}$ sample after an electrochemical micromachining test in aqueous sulphuric acid solution.

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[6] J. Hufenbach et al. (patent application deposited)

**Cooperations:** Partners within the BMWi funded research LuFo: DLR, EADS, MTU, Rolls-Royce; Partners within the BMWi funded research ZIM: TU Chemnitz, quada V+F; Laserschweißdraht GmbH, LPT – Laserpräzisionstechnik GmbH; SWATCH; BOSCH; WIWeB; DIEHL; UMICORE; The NANOSTEEL company; WIELANDWERKE; TU Dresden, Institute of construction materials; IPF Dresden; University of Kaiserslautern and members SPP 1594
Research Area 4
TOWARDS PRODUCTS

Research Topic 4.5

**Concepts and materials for superconducting applications**


**Responsible Director:** L. Schultz

**Summary:** The unique properties of superconducting materials open the way to a wide range of important applications e.g. in the fields of electronics, medicine, research and energy. Low temperature superconducting materials like NbTi and Nb₃Sn are already widely used as high field research magnets and moderate field MRI magnets for medical diagnostics. High temperature superconductors are now on the way to drastically extend the application range towards power systems like motors, cables, fault current limiters as well as ultra-high field magnets and levitation based applications. The central aim of this research topic is to investigate superconducting materials and to develop demonstrator systems that enable the realization of such new applications. This covers the synthesis of high critical current conductors, the controlled pinning enhancement by nano-engineering of superconductors and the realization of demonstration applications to study new technological directions.

**Improved YBCO coated conductors**

The main focus of our work in the last year was on the preparation of thick YBa₂Cu₃O₇-ₓ layers with artificial pinning centers on metallic substrates. Therefore, we used highly textured Ni-W templates with a W content of up to 9.5 at.% prepared by the rolling biaxially textured substrates (RABITS) approach as well as ion-beam textured YSZ layers on stainless steel. The superconducting layers were grown with pulsed laser deposition in a high growth rate scheme. The main emphasis was on the incorporation of BaHfO₃ nanoparticles with different volume content (Fig. 1). It was shown that a significant
improvement of the critical current density in magnetic fields \(J_c(B)\) was achieved using this approach [1]. Alternatively, BaYNbTaO6 nanoparticles were embedded in films on SrTiO3 single crystals. The formation of defined nanorods was observed leading to a significant increase of the pinning for fields parallel to the c-axis.

**MgB2 – Wires and permanent bulk magnets**

An internal Magnesium diffusion described recently in literature was applied as a new technology for the preparation of MgB2-wires. This approach is based on diffusion of metallic Magnesium in the surrounding Boron powder during heat treatment and gives denser filaments in comparison to the classic in-situ technique as basis for higher critical current densities. An engineering critical current density \(J_e\) of 10 kA/cm² at 4.2 K and 5 T was achieved for mono-core wires. These parameters were recently transferred to a seven filament wire.

Last year we reported on high trapped field values of 3.2 T at 15 K measured in MgB2 bulk samples of 1.5 mm thickness (Fig. 2). In a study on the thickness dependence of trapped fields we found that at high temperatures (\(T \sim 24\) K) the optimum sample thickness is \(-1\) mm as for thicker samples only its outer part of \(-1\) mm thickness contributes to the trapped field due to the strong field dependence of the critical current density. At lower temperatures (\(T \sim 15\) K), an insufficient thermal stability prevents a simple thickness scalability of the trapped field which is limited by flux jumps. To overcome this problem, pairs of about 2 mm thick samples separated by a spacer will be used at 15 K in order to increase the trapped field available in a relative large volume between the two samples.

**Superconducting motors and AC losses in YBCO coils**

Pancake coils made from YBCO coated conductors have high critical currents and are attractive for application in superconducting motors. However, the AC losses of YBCO windings are at present too high, especially if the additional effort for the cooling equipment is taken into account. The main contribution to the AC loss of YBCO coils is the hysteretic loss in the superconductor, \(P_{\text{hyst}} \propto B_r^3\), which is basically determined by the large radial component \(B_r\) of the AC self-field in the coil. In superconducting transverse flux motors, a ring shaped double-pancake YBCO coil is used which is enclosed by a soft magnetic yoke with a claw-pole structure. The magnetic flux travelling in transverse direction (perpendicular to the direction of rotation) acts as flux diverter and slightly reduces the radial field in the YBCO coil. We have shown by FEM simulations that this effect can be strongly enhanced by including two ferromagnetic foils close to the plane faces of the YBCO coil. From the simulations, a strong reduction of the radial field \(B_r\) by a factor of three is expected which would reduce the AC loss of the specific motor considered here on values \(P_{\text{hyst}} \leq 20\) W.

**Superconducting magnetic bearings in rotating high-speed textile machines**

Our research activities on small scale levitation applications properties are embedded in the framework of a joint 3-year DFG project with the Institute of Textile Machinery and High Performance Material Technology at the TU Dresden. The work is focused on the implementation and characterization of rotation ring-shaped superconducting magnetic bearings (SMBs) in high-speed textile processing machines for the mass production of short staple yarn. The majority of the short staple yarn produced worldwide today is spun with the traditional ring spinning technique. The productivity of this process depends on the rotational speed of the spindle. It is limited by friction in the so-called ring-traveler twist element (Fig. 3a). During the spinning process the traveler is dragged along the ring-rail by the yarn with up to 30000 rpm. The resulting friction causes wear of the twist element and melting of synthetic yarns at high spindle speeds due to strong heat generation.
The replacement of the ring-traveler twist element by a superconducting magnetic bearing was proposed to overcome this friction-induced productivity limit [2]. SMBs are inherently passive and contact-less bearings consisting, in this case, of a permanent-magnetic NdFeB ring acting as yarn-driven traveler and a stationary superconducting $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ ring cooled on 77 K in a cryostat (Fig. 3b). With a first prototype of our SMB twist element in an open bath cryostat, several hundred meters of yarn were spun and the yarn quality was found to be comparable to conventional ring spun yarn [3]. Therefore, a ring-shaped flow-through cryostat was developed and built in cooperation with our industrial partner evico GmbH. Superconducting rings were assembled from preselected bulks, prepared at the IFW by a melt texturing technique. Simultaneously we started to investigate experimentally as well as describe theoretically the static and dynamic behavior of the SMB, e.g. forces, displacements and precession, with respect to the ring spinning process [4].

**Large Scale Application: SupraTrans II**

After the completion, the test drive facility SupraTrans II is used now for scientific investigation. Particular emphasis lies on the study of the behavior under practical operation conditions and the development of new components such as electromagnetic tracks and fast switchable electromagnetic turnouts. First result of a PhD work on such new system components is a model of an electromagnetic track using superconducting tapes to create the magnetomotive force needed (Fig. 4). Simultaneously, the test
drive facility is used for a general dissemination of superconductivity to the wider public (pupils, students, vocational training etc.) as well as for professional presentations to contact potential users of this new technology.

Furthermore, a PROBRAL-Project together with the Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering (COPPE) at the Federal University of Rio de Janeiro was started in 2014. This institute opened its own straight outdoor superconductive levitation line, the MagLev Cobra. The aim of the exchange project is to examine and compare the driveway characteristics of the SupraTrans and the MagLev Cobra, which are different in design, as well as to study the behavior of such systems for an outdoor application and on curved tracks.


Funding: EU (EuroTapes), DFG, BMBF (Project Diamant), DAAD PPP PROBRAL

Cooperations: Bruker HTS, Alzenau, Germany; THEVA GmbH, Ismaning, Germany; University of Cambridge, United Kingdom; ICMAB Barcelona, Spain; University of Vienna, Austria; COPPE/UFRJ, Rio de Janeiro, Brazil; evico GmbH, Dresden, Germany; Institute of Textile Machinery and High Performance Material Technology at the TU Dresden; Festo AG & Co KG, Esslingen, Germany; KIT, Karlsruhe, Germany; Siemens CT Erlangen, Germany; IEE Bratislava (SAS), Slovakia
Publications 2014

Monographs and Editorships

Journal Papers


39) J. Brand, A. Stunault, S. Wurmehl, L. Harnagea, B. Buechner, M. Meven, M. Braden, **Spin susceptibility in superconducting LiFeAs studied by polarized neutron diffraction**, Physical Review B 89 (2014) Nr. 4, S. 45141/1-5.


V.V. Fisun, O.P. Balkashin1, O.E. Kvintitskaya, I.A. Korovkin, N.V. Gamayunova, S. Aswartham, S. Wurmehl, Y.G. Naidyuk, Josephson effect and Andreieff reflection in Ba1-xNaxFe2As2 (x=0.25 and 0.35) point contacts, Low Temperature Physics 40 (2014) Nr. 10, S. 919-924.


103) E.J. Guo, R. Roth, S. Das, K. Doerr, Strain induced low mechanical switching force in ultrathin PbZr0.2Ti0.8O3 films, Applied Physics Letters 105 (2014) Nr. 1, S. 12903/1-5.


121) A. Ichinose, I. Tsukada, F. Nabeshima, Y. Imai, A. Maeda, F. Kurth, B. Holzapfel, K. Iida, S. Ueda, M. Naito, Induced lattice strain in epitaxial Fe-based superconducting films on CoF2 substrates: A comparative study of the microstructures of SmFeAs(O,F), Ba(Fe2O)2As2, and FeTe0.5Se0.5, Applied Physics Letters 104 (2014) Nr. 12, S. 122603/1-5.


140) H.Y. Jung, S. Yi, *Nonocrystalization and soft magnetic properties of Fe23M6 (M = Co or B) phase in Fe-based bulk metallic glass, Intermetallics 49 (2014), S. 18-22.


N. Mattern, J.H. Han, K.G. Pradeep, K.C. Kim, E.M. Park, D.H. Kim, Y. Yokoyama, D. Raabe, J. Eckert, Structure of rapidly quenched (Cu0.5Zr0.5)100xAg alloys (x = 0-40 at. %), Journal of Alloys and Compounds 607 (2014), S. 285-290.


228) M. Oschatz, L. Borchardt, K. Pinkert, S. Thieme, M.R. Lohe, C. Hoffmann, M. Benusch, F.M. Wisser, C. Ziegler, L. Giebeler,

231) J.M. Park, K.R. Lim, E.S. Park, S. Hong, K.H. Park, J. Eckert, D.H. Kim,

222) R. Niemann, J. Kopecek, O. Heczko, J. Romberg, L. Schultz, S. Faehler, E. Vives, L. Manosa, A. Planes,

223) I.V. Okulov, M. Boenisch, U. Kuehn, W. Skrotzki, J. Eckert,

220) E. Nazarova, K. Buchkov, S. Terzieva, K. Nenkov, A. Zahariev, D. Kovacheva, N. Balchev, G. Fuchs,


230) S. Oswald, U. Vogel, J. Eckert, ARXPS measurement simulation for improved data interpretation at complex Ta/Li-niobate interfaces, Surface and Interface Analysis 46 (2014), S. 1094-1098.


W. Si, I. Moench, C. Yan, J. Deng, S. Li, G. Lin, L. Han, Y. Mei, O.G. Schmidt, A single rolled-up Si tube battery for the study of electrochemical kinetics, electrical conductivity, and structural integrity, Advanced Materials 26 (2014), S. 7973-7978.

W. Si, X. Sun, X. Liu, L. Xi, Y. Jia, C. Yan, O.G. Schmidt, High areal capacity, micrometer-scale amorphous Si film anode based on nanostructured Cu foil for Li-ion batteries, Journal of Power Sources 267 (2014), S. 629-634.


324) U. Vogel, T. Gemming, J. Eckert, S. Oswald, Analysis of surface pre-treatment for SAW substrate material (LiNbO3) and deposited thin films of Ta/Tr using ARXPS, Surface and Interface Analysis 46 (2014), S. 1033-1038.


Contributions to Conference proceedings and monographs


Invited talks


35) J. Eckert, Improving the ductility of bulk metallic glasses by mechanical treatment, Global Research Laboratory Korea- Germany Workshop on Bulk Metallic Glasses and Nanostructured Materials, Jeong Seon/ Korea, 22.8.14 (2014).
44) J. Fink, ARPES experiments on conventional and unconventional superconductors, SpecNovMat Workshop SLS, Passugg-Araschgen/ Schweiz, 27.2.-3.3.14 (2014).
49) V.M. Fomin, Topological effects in physical properties of quantum rings, Seminar, Department of Electrical Engineering, University of California, Riverside, California/ USA, 13.3.14 (2014).
53) V.M. Fomin, Quantum rings: A unique playground for topological effects from doubly connectedness to one sidedness, EMN Spring Meeting, Las Vegas, Nevada/ USA, 27.2.-2.3.14 (2014).


77) V. Kataev, *Interplay of site disorder and magnetic frustration in the quantum spin magnet CoAl2O4*, Seminar at the Molecule Photonscience Research Center, Kobe University, University of Kobe, Kobe/ Japan, 4.11.14 (2014).


89) D. Makarov, *Magnetic tubular architectures*, Seminar, Department of Physics, Universidad Tecnica Federico Santa Maria, Valparaiso/ Chile, 24.3.14 (2014).

90) D. Makarov, *Spin-orbit coupling effects in magnetic sandwiches*, Seminar, Department of Physics, Universidad Tecnica Federico Santa Maria, Valparaiso/ Chile, 24.3.14 (2014).


92) D. Makarov, *Magnetism in curved surfaces*, Seminar, Department of Physics, Universidad Tecnica Federico Santa Maria, Valparaiso/ Chile, 18.3.14 (2014).

93) D. Makarov, *Imperceptible magnetoelectronics*, Seminar, Department of Physics, Universidad Tecnica Federico Santa Maria, Valparaiso/ Chile, 26.3.14 (2014).

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94) D. Makarov, Flexible Hall effect sensors for automotive applications, Seminar, Department of Physics, Universidad Tecnica Federico Santa Maria, Valparaíso/ Chile, 26.3.14 (2014).
101) V. Neu, Epitaxial Rare-Earth Cobalt thin films and multilayers: tuning anisotropies and functionality, Seminar at IMDEA Nanoscience, Madrid/ Spain, 5.11.14 (2014).
102) V. Neu, Principles and possibilities of quantitative magnetic force microscopy, Seminar at the Instituto de Ciencia de Materiales de Madrid, Madrid/ Spain, 4.11.14 (2014).


169) J. van den Brink, *Resonant Inelastic X-ray scattering on high Tc cuprates, iron pnictides and magnetic iridates*, Workshop Magnetism, Bad Metals and Superconductivity: Iron Pnictides and Beyond, KITP Santa Barbara/ USA, 10.10.14 (2014).


## Patents 2014

### Issues of Patents

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<td>Akustisches Oberflächenbauelement (07.08.2014)</td>
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<td>Miroslava Sakaliyska, Jürgen Eckert, Kumar Babu Sureddi, Sergio Scudino</td>
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<td>Formkörper aus einem aluminiumhaltigen Verbundwerkstoff und Verfahren zu seiner Herstellung (30.10.2014)</td>
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<td>Markus Herklotz, Jonas Weiß, Lars Giebeler, Michael Knapp</td>
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Priority Patent Applications

11401 Verfahren zur Herstellung von amorphen metallischen Partikeln (21.03.2014)
   Inventors: Uta Kühn, Sven Donath, Michael Franke

11402 Verfahren zur Herstellung der Beweglichkeit von immobilen Zellen (31.01.2014)
   Inventors: Oliver G. Schmidt

11406 Anodenmaterial für Lithium-Ionen-Batterien (01.04.2014)
   Inventors: Maik Scholz, Rüdiger Klingeler, Marcel Haft, Sabine Wurmehl, Silke Hampel, Franziska Hammerath, Bernd Büchner

11407 Wandler für akustische Oberflächenwellen mit einer natürlichen Vorzugsrichtung bei der Wellenabstrahlung (09.04.2014)
   Inventors: Günter Martin

11411 Verfahren zur Herstellung von sphärischen Silizium-Kohlenstoff-Nanokompositen, sphärische Silizium-Kohlenstoff-Nanokomposite und deren Verwendung (04.06.2014)
   Inventors: Tony Jaumann, Lars Giebeler, Jürgen Eckert

11413 Hochfeste, mechanische Energie absorbierende und korrosionsbeständige Formkörper aus Eisenlegierungen und Verfahren zu deren Herstellung (01.09.2014)
   Inventors: Josephine Zeisig, Julia Kristin Hufenbach, Uta Kühn, Jürgen Eckert

11414 Batterieträger (20.06.2014)
   Inventors: Markus Herklotz, Jonas Weiß, Lars Giebeler, Michael Knapp

11415 Ultrakompakter Mikrokondensator und Verfahren zu seiner Herstellung (05.11.2014)
   Inventors: Daniel Grimm, Martin Bauer, Oliver G. Schmidt

11416 Verfahren zur Rückgewinnung von Metallen der Seltenen Erden aus SE-Fe-enthaltendem Material (22.08.2014)
   Inventors: Martina Moore, Annett Gebert, Mihai Stoica, Wolfgang Löser

11418 Capacitor and Process for producing thereof (26.08.2014)
   Inventors: Daniel Grimm, Oliver G. Schmidt, Ivoyl Koutsaroff, Shoichiro Suzuki, Koichi Banno

11419 Capacitor and Process for Producing thereof (26.08.2014)
   Inventors: Daniel Grimm, Oliver G. Schmidt, Shiochiho Suzuki, Akira Ando, Koichi Banno

11420 Verfahren zur Herstellung von teil- oder vollkristallinen, metastabilen Materialien und teil- oder vollkristalline, metastabila Materialien (23.10.2014)
   Inventors: Simon Pauly, Konrad Kosiba, Uta Kühn, Jürgen Eckert

11424 Verfahren und Vorrichtung zur Ermittlung von Kraftfeldern, Kraftfeldgradienten, Materialeigenschaften oder Massen mit einem System aus gekoppelten, schwingungsfähigen, balkenartigen Komponenten (12.12.2014)
   Inventors: Christopher Reiche, Thomas Mühl, Julia Körner

11426 Kompakter Kondensator und Verfahren zu seiner Herstellung (13.10.2014)
   Inventors: Oliver G. Schmidt

11429 Verfahren zur Herstellung eines aufgerollten elektrischen oder elektronischen Bauelementes (24.11.2014)
   Inventors: Daniel Grimm, Dmitriy Karnauschenko, Martin Bauer, Daniil Karnauschenko, Denys Makarov, Oliver G. Schmidt

11430 Vorrichtung zur Flüssigkeitszerstäubung und Verfahren zu ihrer Herstellung (06.11.2014)
   Inventors: Andreas Winkler, Stefan Harazim, Jürgen Eckert, Oliver G. Schmidt

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**PhD Theses**

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Manuela Erbe Chemische Lösungsabscheidung von (Y,6d)Ba2Cu3O7-δ-Dünnschichten: Untersuchungen zur Eigenschaftsoptimierung, TU Dresden

Piter Gargarella Phase formation, thermal stability and mechanical behaviour of TiCu-based alloys, TU Dresden

Prashanth Konda Gokuldoss Selective laser melting nof TiCu-based alloys, TU Dresden

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Junhee Han Phase separation and structure formation in gadolinium based liquid and glassy metallic alloys, TU Dresden

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Katja Pinkert Mesoporöse Kohlenstoffmaterialien und Nanokomposite für die Anwendung in Superkondensatoren, TU Dresden

Ummethala Raghunandan Growth and field emission characteristics of MWCNT's on different substrates, TU Dresden

Jan Romberg Feinlagige und feinkristalline Titan/Aluminium-Verbundbleche, TU Dresden

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Ronny Schlegel Untersuchung der elektronischen Oberflächeneigenschaften des stöchiometrischen Supraleiters LiFeAs mittels Rastertunnelmikroskopie und -spektroskopie, TU Dresden

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Khomenko Vladislav  Nanoskalige Strukturzeugung durch elektroneninduzierte Graphitisierung in diamantartigen Kohlenstoffschichten, TU Bergakademie Freiberg
Kranz Ludwik  Transportmessungen an kleinen Einkristallen, TU Dresden
Kühne Tim  Spin-polarised scanning tunneling microscopy and spectroscopy on ultra-thin iron films, TU Dresden
Müller Eric  Spektroskopische Untersuchungen an dotierten Picen-Filmen, TU Dresden
Nohr Markus  Einkristallzucht und Charakterisierung von aromatischen Ladungstransfer-Salzen, HTW Dresden
Prateek Kumar Aharonov-Bohm  Oscillations in a long-perimeter Bi2Te3 nanowire, TU Dresden
Christian Quandt  Entwicklung einer Anlage für magnetunterstütztes Tempern und Kristallisieren, HTW Dresden
Till Meißner  Konstruktion und Entwicklung eines Kryo-Magnetkraftmikroskops, HTW Dresden
Vignesh Mahalingham  Fabrication and investigations of vertically stacked quantum dot devices, TU Chemnitz
Michael Zopf  Coherent strain tunable single photon sources, TU Dresden
Hany Abushall  Double jet engines, TU Dresden
Robert Keil  Resonance fluorescence from GaAs/AlGaAs quantum dots, TU Dresden
Karsten Rost  Optimisation of an electrochemical etching approach for flexible Hall sensorics, TU Dresden
Anna Brunner  Untersuchungen zur Flussführung in nicht-orientiertem Elektroblech, TU Dresden
Christoph Konczak  Elektrochemische Präparation und Charakterisierung von FePd-Schichten für Formgedächtnisanwendungen, TU Dresden
Dominik Markó  Tiefenempfindliche Kerr-Mikroskopie an fehlorientierten FeSi-Oberflächen, TU Dresden
Christian Becker  Untersuchung der dynamischen Oberflächen- und Volumenmagnetisierung weichmagnetischer Bänder, TU Dresden
Stefan Richter  Einfluss uniaxialer Spannungen auf die Eigenschaften Fe-basierter Supraleiterschichten, TU Dresden
Calls and Awards

Calls on Professorships

Dr. Maria Daghofer       Univ. Stuttgart
Prof. Dr. Jürgen Eckert  Montan Univ. Leoben
Dr. Jochen Geck          Univ. Salzburg

Appointments as Adjunct, Honorary, Deputy and Associated Professorships

Prof. Dr. Jens Freudenberger   Bergakademie TU Freiberg (Deputy Professorship)

Awards

Prof. Dr. Manfred Hennecke   Bundesverdienstkreuz Erster Klasse
Prof. Dr. Oliver G. Schmidt  International Dresden Barkhausen Award
Prof. Dr. Jürgen Eckert      DGM Preis
Dr.-Ing. Alexander Kauffmann DGM Nachwuchspreis 2014
Dr.-Ing. Alexander Kauffmann Förderpreis 2014 des Deutschen Kupferinstituts
Dr. Saicharan Aswartham     DGKK-Nachwuchsforscherpreis 2014
Martin Grönke               VDI Nachwuchspreis
Josephine Zeisig            Poster Award des DGM Nachwuchsforums

IFW Awards

Dr. Alexey Popov           IFF Research Award 2014
Dr. Karin Leistner         IMW Research Award 2014
Dr. Lars Giebeler          IKM Research Award 2014
Dr. Fei Ding               IIN Research Award 2014
Dr. Tom Marr               Tschirnhaus-Medal of the IFW for excellent PhD theses
Dr. Jan Engelmann          Tschirnhaus-Medal of the IFW for excellent PhD theses
Dr. Jan Trinkauf           Tschirnhaus-Medal of the IFW for excellent PhD theses
Dr. Inge Lindemann         Tschirnhaus-Medal of the IFW for excellent PhD theses
Dr. Alexander Kauffmann    Tschirnhaus-Medal of the IFW for excellent PhD theses
Dr. Lars Kühn              Tschirnhaus-Medal of the IFW for excellent PhD theses
Dr. Ronny Schiegel         Tschirnhaus-Medal of the IFW for excellent PhD theses
Dr. Piter Gargarelle       Tschirnhaus-Medal of the IFW for excellent PhD theses
Dr. Julia Hufenbach        Tschirnhaus-Medal of the IFW for excellent PhD theses
Scientific conferences and IFW colloquia

Conferences

Feb. 25 – March 1, 2014  BioTiNet Winter school 2014, Vienna, Austria
March 27/28, 2014  Kick-Off Meeting of the SPP 1458 “High Temperature Superconductivity in Iron Pnictides”, 2nd funding period, IFW Dresden
March 30 – Apr. 4, 2014  DPG-Frühjahrstagung der Sektion Kondensierte Materie (SKM) Dresden
May 4 – 8, 2014  IEEE International Magnetics Conference (Intermag), Dresden
May 5, 2014  Symposium “Energy assisted magnetic recording beyond 1TB/in2” at the INTERMAG 2014 conference, Dresden
July 17 – 18, 2014  Workshop “NMR, μSR, Mössbauer spectroscopies in the study of Fe-based and other unconventional high-Tc superconductors”, IFW Dresden
Sept. 12/13, 2014  Final IRON-SEA meeting, IFW Dresden
Nov. 5 – 8, 2014  BioTiNet Final Meeting, Dresden

IFW Colloquium

30.01.2014  Prof. Dr. Rudolf Schäfer, IFW Dresden, IEEE Distinguished Lecturer, Magneto-Optic Analysis of Magnetic Microstructures
27.03.2014  Prof. Dr. Peter Hirschfeld, University of Florida, Department of Physics, Fe-based Superconductors: What have we learned?
24.04.2014  Dr. Jack J.W.A. van Loon, DESC - Dutch Experiment Support Center, Amsterdam, The Human Hypergravity Habitat, H3 - A ground based facility for Space Explorations and General Human Health Research in Ageing and Obesity
15.05.2014  Prof. Dr. J.M.D. Coey Trinity College, Dublin, Ireland, Gas bubbles in electrolysis. How could magnetic fields help?
## Guests and Scholarships

**Guest scientists** (stay of 4 weeks and more)

<table>
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<tr>
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<td>Ryu, Wook Ha</td>
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Guest stays of IFW members at other institutes

Oliver Schmidt 27.10. – 05.11.2014, Shanghai/China – Kooperation Fudan Univ.
Micheal Melzer 1.11. – 10.11.2014, Honolulu/Hawaii/USA – MMM Conference
Yongheng Huo 28.10. – 08.11.2014 Heifei/China – Cooperation with Univ. of Science and Technology China
Denys Makarov 15.03. – 29.03.2014 Valparaiso/Chile – Universidad Technica Frederico Santa Maria Departamento de Fisica
Robert Streubel 10.03. – 26.03.2014 Berkeley/USA – Advanced Light Source Lawrence Berkeley National Laboratory, Measuring time
Vladimir Fomin 03.03. – 16.03.2014 Riverside/USA – Research Cooperation UC Riverside
Matthew Jorgensen 03.04. – 15.04.2014 Utah/USA – Research Cooperation University of Utah
Stefan Hameister 26.09. – 03.10.2014, Saarbrücken, Highlights der Physik,
Michael Hering 26.09. – 03.10.2014, Saarbrücken, Highlights der Physik
Ivan Soldatov 14.02. – 24.02.2014, Jekaterinburg/Russland, International Winterschool on Physics,
Tilo Espenhahn 13.01. – 23.03.2014, Univ.Niigata/Japan, Students’ exchange
Fritz Kurth 01.05. – 11.05.2014, NHMFL, Tallahassee/USA, measurements
Tilo Espenhahn 28.09. – 08.11.2014, Rio de Janeiro/Brasilien, PPP Probral, Univ. exchange program
Anne Berger 27.09. – 28.11.2014, Rio de Janeiro/Brasilien, PPP Probral, Univ. exchange program
Lars Kühn 26.09. – 12.10.2014, Rio de Janeiro/Brasilien, PPP Probral, Univ. exchange program
Prof. Rudolf Schäfer 01.10. – 12.10.2014, Oak Ridge National Lab, Detroit/USA, invited talks and lectures
Vamshi Mohan Katukuri 03. – 09.01.2014, International Centre for Theoretical Sciences, Bangalore India, Winter school on „Strongly correlated systems From models to materials”
Stefanos Kourtis 19.03. – 22.04.2014, Boston University, Collaboration on three-dimensional topologically ordered states
Stefanos Kourtis 23.04. – 06.05.2014, University of Leeds, Great Britain, Studies on Majorana-fermion lattices in three dimensions
Ekaterina Plotnikova 05. – 28.08.2014, Ecole de Physic de Houches, Summer School: Topological aspects of condensed matter physics
Judit Romhányi 15.09. – 17.10.2014, Budapest University of Technology and Economics, Department of Physics, Scientific collaboration
Carmine Ortix 03. – 26.11.2014 University of Utrecht, Collaboration on theory of graphene nanostructures
Jeroen van den Brink 26.10. – 20.11.2014 University of California, Santa Barbara, Workshop „Iron pnictides and beyond” at Kavli-Institute for Theoretical Physics (KITP) and research visit
Ekaterina Plotnikova 28.10. – 21.11.2014 University of California, Santa Barbara, Workshop „Iron pnictides and beyond” at Kavli-Institute for Theoretical Physics (KITP) and research visit
Cristina Gonzalez Gago 13.09. – 29.09.2014, University of Oviedo, Spain, training course and GD-ToF-MS measurements
Lixia Xi 16.06. – 06.07.2014, Foundry Research Institute Krakau, Poland, DAAD-PPP
Lixia Xi 15.11. – 24.12.2014, Foundry Research Institute Krakau, Poland, DAAD-PPP
Junhee Han 29.08. – 13.09.2014, Yonsei University Seoul, Korea
Mariana Calin 03.04. – 26.04.2014, Univ. Politehnica Timisoara & Univ. Politehnica Bucuresti, Timisoara/Bukarest Romania, Teaching and Research activities

Bönisch Mathias 25.02. – 14.03.2014, Faculty for Physics, Vienna, Austria

Bastien Dassonneville 04.08. – 29.08.2014, École de Physic Les Houches, France, Summer School

Deng Qingming 08.01.2013 – 10.06.2014, Nagoya Univ. Japan, Research cooperation on the formation mechanism of endohedral metallofullerenes

Alexander Fedorov 09.01. – 24.01.2014, Elettra Sincrotrone Trieste, Italy, Measurements

Alexander Fedorov 09.03. – 24.03.2014, Bessy Berlin, Measurements

Grafe Hans-Joachim 14.03. – 16.05.2014, Univ. of California, Davis, California, USA, Research stay

Sirko Kamusella 01.06. – 22.07.2014, Paul Scherrer Institut Villigen, Switzerland, Measurements at SwissMuonSource

Wolf Schottenhamel 26.01. – 16.02.2014, Brookhaven National Laboratory, New York, USA, Measurements

Yulia Krupskaya 01.07.2013 – 30.06.2015, DPMC University of Geneva, Switzerland

Zhonghao Liu 01.10.2013 – 31.08.2014, HZB Berlin at Bessy II, measurements
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## Research organization of IFW Dresden

### Institute for Solid State Research (IFF)

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<td>Electron spectroscopy and microscopy</td>
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### Institute for Metallic Materials (IMW)

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### Institute for Complex Materials (IKM)

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Date: 01/2015