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CENIDE
CENTER FOR NANOINTEGRATION DUISBURG-ESSEN

DFG
Deutsche Forschungsgemeinschaft

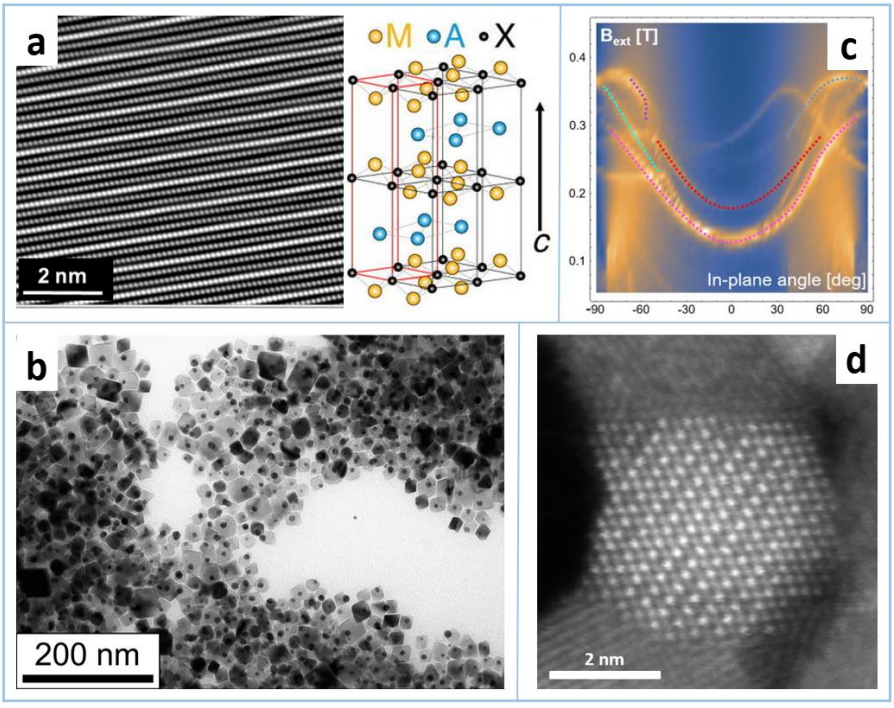
11th International Workshop
on nanomagnetism and its novel applications
SpinS-2019

DUISBURG / MÜLHEIM AN DER RUHR

2 – 4 OCTOBER 2019

Workshop organizers:
Prof. Michael Farle
Dr. Katharina Ollefs
Dr. Anna Semisalova
(University of Duisburg-Essen)

Venue:
"Die Wolfsburg" Academy,
Falkenweg 6,
45478 Mülheim an der Ruhr,
Germany



Welcome to SpinS-2019!

The international Workshop SpinS-2019 is the continuation of a series of international meetings regularly held since 2009 by Universities in Europe (France, Spain, Portugal, Germany). We, Michael Farle, Katharina Ollefs and Anna Semisalova, are honored to organize the meeting in 2019 at the University of Duisburg-Essen.

Following the tradition, the program of SpinS-2019 focusses on nanomagnetism and its novel applications. It covers the most recent experimental and theoretical research developments related to spin phenomena in nanoscale systems as well as the design, properties and applications of magnetic nanomaterials. Over the last few years nanomagnetism phenomena have been playing a vital role in the development of several emergent technologies based on spin-orbit torques, ultrafast spin dynamics in THz frequency range, magnonics, magnetoacoustics, magnetic cooling as well as novel materials like shell-ferromagnets, MAX phases (including 2D MXenes), and nanohybrids for theranostics applications.

The purpose of workshop SpinS-2019 is to provide an interdisciplinary platform for experts with different specializations ranging from materials science to physics and chemistry to meet and discuss their most recent achievements. We hope that the workshop will be the starting point of new collaborative research work in the near future. By our program, we tried to connect experts in fabrication and imaging of 2D and 3D magnetic nanostructures with scientists working towards various application areas – from spin dynamics and magnetic memory to additive manufacturing and biomedicine as well as experts in theory.

We are thankful to all the participants for your interest in the SpinS-2019 workshop, and we hope you find the program exciting and promoting new collaborations. We are pleased to host two 2019 IEEE Magnetics Society Distinguished Lecturers – Prof. Hyunsoo Yang (National University of Singapore) and Prof. Hari Srikanth (University of South Florida) for their interest to participation in the Workshop this year. The members of the international advisory committee – Hamid Kachkachi (Perpignan, France), Oscar Iglesias (Barcelona, Spain), Ulrich Nowak (Konstanz, Germany), Davide Peddis (Rome, Italy), David Schmool (Versailles, France), Vasily Temnov (Le Mans, France), Francois Vernay (Perpignan, France) and Ulf Wiedwald (Duisburg, Germany) are sincerely acknowledged for the suggestions on the Workshop topics.

We would like to express our gratitude to the Center for Nanointegration Duisburg-Essen (CENIDE) and Deutsche Forschungsgemeinschaft (DFG) for financial support as well as the European Magnetism Association (magnetism.eu) for informational assistance. Finally, we would like to thank Sabina Grubba and Michael Vennemann (UniDuE) for their help in coordination of the registration process and maintenance of the website.

We wish all participants of SpinS-2019 productive meeting sessions with lively and stimulating discussions in the hospitable atmosphere of “Die Wolfsburg” Academy as well as a great time in Metropole Ruhr!

Michael Farle, Katharina Ollefs, Anna Semisalova

The following images were used for illustration of the front page:
a) atomically layered Mn_2GaC MAX phase thin film resolved with HAADF/STEM, and corresponding crystal structure. Courtesy by Novoselova et al. (2018), Flatten et al. (2019).
b) Fe_3O_4-Au hybrid nanoparticles for theranostics applications. Courtesy by Efremova et al. (2018).
c) micromagnetic simulation and experimentally measured ferromagnetic resonance modes of magnetite nanoparticles chain from single magnetotactic bacteria. Courtesy by Feggeler, Zingsem, Winklhofer et al. (2019).
d) $L1_0$ $Fe_{25}Pt_{50}Cu_{25}$ nanoparticle from gas phase. Courtesy by Acet, Spasova and Elsukova (2012).

	Wednesday, Oct. 2	Thursday, Oct. 3	Friday, Oct. 4
09:00-09:30		**Hyunsoo Yang** Spin-orbit technologies: from magnetic memory to terahertz generation **(IEEE DL 2019)**	**Florent Tournus** Specific Properties of FePt nanoparticles and self-organization on graphene
09:30-10:00			**Naëmi Leo** Engineering Thermal Relaxation Pathways for Nanomagnetic Computation
10:00-10:30		**Yu Fu** Spin-to-charge current interconversion by Edelstein effect in 2D materials using FMR spin pumping method	**Denis Markelov** Hollow Core Dendrimers: Theory, Simulations, and NMR Experiments
10:30-11:00		**Coffee break**	**Coffee break**
11:00-11:30		**Sebastian Wintz** Spin textures and spin waves as seen by x-ray microscopy	**Maxim Abakumov** Application of magnetic nanoparticles in cancer theranostics
11:30-12:00		**Alexandr Alekhin** Ultrafast dynamics at optically-excited magnetic meta-surfaces	**Oscar Iglesias** Aggregates and dipolar interactions in nanoparticle assemblies for hyperthermia
12:00-12:30	**Arrival, Registration**	**Daniel Marko** Tunable ferromagnetic resonance in coupled trilayers with crossed in-plane and perpendicular magnetic anisotropies	**Makis Angelakeris** Magnetic Particle Hyperthermia: Current trends and prospects
12:30-13:00		**Ruslan Salikhov** Magnetic relaxation in ferromagnetic metallic films with enhanced perpendicular anisotropy	**Aram Manukyan** Synthesis and Characterization of Carbon Coated Fe-Fe_3C "Core-Shell" Nanoparticles for Magnetic Hyperthermia
13:00-14:00	**Lunch**	**Lunch**	**Lunch**
14:00-14:30	**Dieter Suess** Low Noise TMR - Vortex Sensors and 3d Printed Permanent Magnets for Magnetic Sensor Applications	**Hari Srikanth** Tuning magnetic anisotropy in nanostructures for biomedical applications **(IEEE DL 2019)**	**Departure**
14:30-15:00	**Luka Skoric** Advanced fabrication and magnetometry of nanostructures with complex 3D geometries		
15:00-15:30	**Aleksandra Titova** Spin-transport in magnetic tunnel junctions with a zero-moment half-metallic electrode	**Hamid Kachkachi** Study of interacting assemblies of nanomagnets: Competing effects	
15:30-16:00	**Daniel Wegner** Magnetic order in neodymium metal – a new type of spin glass?	**Heiko Wende** Magnetic relaxation dynamics in soft matter nanoparticle composite systems	
16:00-16:30	**Coffee break**	**Coffee break**	
16:30-17:00	**Ulrich Nowak** Modeling Skyrmion diffusion in thin film multilayers	**Verónica Salgueiriño** Magnetooptical Activity of Cobalt Ferrite Nanoparticles confined in Silica Capsules and modified by One Single Gold Nanoparticle	
17:00-17:30	**Ulrike Ritzmann** Skyrmiogenesis: Skyrmion–antiskyrmion asymmetry from pair generation under spin-orbit torques	**Sara Laureti** EXAFS characterization of magnetic nanostructures	
17:30-18:00	**Iuliia Novoselova** Magnetic MAX phases	**Poster session**	
18:00-18:30	**Benjamin Zingsem** Nanomagnonic properties of Biogenic magnetite		
18:30-19:30	**Dinner**	**GALA DINNER**	

Low Noise TMR - Vortex Sensors and 3d Printed Permanent Magnets for Magnetic Sensor Applications

Dieter Suess, Christian Huber

Faculty of Physics, University of Vienna, Vienna

Within the talk I will review our activity dedicated to the newest developments of the CD-lab "Advanced magnetic sensing and materials" with is done in cooperation with Infineon. One highlight that will be presented is the significant reduction of the noise in tunneling magnetoresistance sensors (TMR) that are used for speed wheel sensors for ABS systems in cars [1]. We will present a disruptive sensor design utilizing a magnetic vortex state in the free layer in order to overcome the fundamental phase noise problem. Due to the nature of this topological protected state it intrinsically does not show the dominant noise of state of the art xMR sensors. A further advantage of this vortex sensor is a significant increased linear range as compared to elliptical sensors.

In the second part of the talk, I will give a review about our activity in additive manufacturing. We developed magnetic filaments that can be used in commercial 3D printers that allows to print polymer bonded NdFeB magnets [2]. We will present results on aligning anisotropic ferrite particles during printing that could allow in the future to realize magnets with locally varying magnetization directions such as Halbach arrays or undulators.

[1] Suess, Dieter, et al. "Topologically protected vortex structures for low-noise magnetic sensors with high linear range." Nature Electronics 1.6 (2018): 362.

[2] Huber, C., et al. "3D print of polymer bonded rare-earth magnets, and 3D magnetic field scanning with an end-user 3D printer." Applied Physics Letters 109.16 (2016): 162401.

Advanced fabrication and magnetometry of nanostructures with complex 3D geometries

L. Skoric[1], D. Sanz-Hernández[1], F. Meng[1], C. Donnelly[1], A. Fernández-Pacheco[1,2]

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The extension of nanomagnetism to three dimensions is proposed as an exciting route to study new physical effects, such as the emergence of new spin textures and magneto-chiral phenomena, with the prospective of being exploited in future technologies [1, 2]. Whereas a significant amount of work has been so far devoted to simulating 3D nanostructures, its fabrication and characterization has proven to be very challenging, and very few of these systems have been experimentally investigated.

Our group has been recently developing new fabrication and characterization methods specifically tailored for the study of 3D nanostructures, which made it possible to control the advanced motion of domain walls in 3D straight nanowires [3, 4].

Here, we will present recent advances in this realm, which now enable us to create and probe nanomagnets with more complex 3D geometries. First, we will present recent work dedicated to the 3D printing of nanomagnets using Focused Electron Beam Induced Deposition (FEBID). Based on the effective FEBID continuum model [5] and proximity effect corrections, we have developed an algorithm with the capability of modelling the deposition and defining beam scanning patterns for arbitrary 3D geometries [6]. The algorithm performance has been demonstrated in different electron microscopes and precursor gases, allowing us to create 3D nanomagnets with a wide range of geometries directly from CAD files (See Fig. 1).

Complementing nanofabrication, we will present a new Kerr magneto-optical setup with the ability to probe 3D magnetic nanostructures, by exploiting the dark-field MOKE (dfMOKE), a technique that we have recently developed [3]. The unprecedented flexibility of the system to characterize these newly accessible 3D geometries will be demonstrated, thanks to the combination of mobile optics and full-3D vector magnetic fields (Fig. 2).

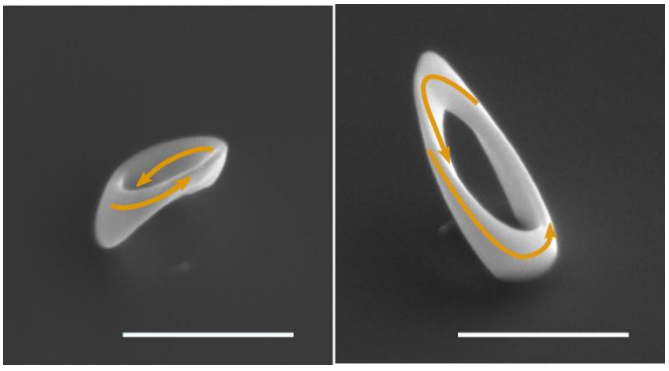

Figure 1. Example of a Cobalt Möbius strip deposited with FEBID. Adapted from [6]. Scale bar is 1μm.

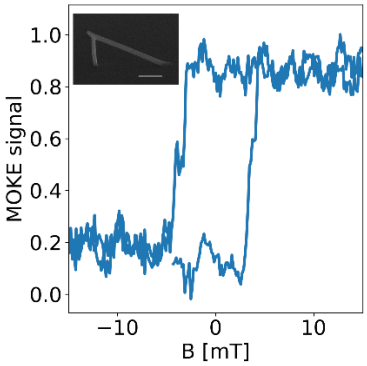

Figure 2. Example of a structure deposited with FEBID. Scale bar is 1μm.

[1] A. Fernández-Pacheco et al., Nat. Commun., vol. 8, 15756 (2017).
[2] R. Streubel et al., J. Phys. Appl. Phys., vol. 49, no. 36, p. 363001, 2016.
[3] D. Sanz-Hernández et al., ACS Nano 2017 11 (11), 11066-11073
[4] D. Sanz-Hernández et al., Nanomaterials 2018, 8(7), 483
[5] M. Toth et al., Beilstein J. Nanotechnol. 2015, 6, 1518–1540
[6] arXiv:1908.10819 [cond-mat.mes-hall]

Spin-transport in magnetic tunnel junctions with a zero-moment half-metallic electrode

Aleksandra Titova[1,2], Ciaran Fowley[1], Yong-Chang Lau[3], Kiril Borisov[3], Gwenael Atcheson[3], Plamen Stamenov[3], Michael Coey[3], Karsten Rode[3], Jürgen Lindner[1], Jürgen Fassbender[1,2], Alina Maria Deac[1]

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The Big Data revolution has spurred the social need for transmitting ever-larger amounts of data and increasing data transmission speed. To be successful, cheap and compact THz-transmitters/receivers have to be created. From the field of spintronics, spin-transfer-torque nano-oscillators (STNOs) may offer a solution for this demand, provided that their output frequency can be increased. In such devices, a spin-polarized current induces magnetization dynamics at frequencies of the same order of magnitude as their resonance frequencies. The operating frequencies for current STNOs based on typical transition metal-based ferromagnets and their derivatives lie in the GHz range, as a consequence of their low magnetic anisotropy and high magnetization. On the other hand, ferrimagnetic materials with ultra-high effective anisotropy fields are very promising, as they exhibit magnetic resonances of several hundred GHz, with antiferromagnetic modes in the THz. By integrating such materials into STNOs, sub-THz and even THz wireless emission may be achieved. In order to obtain high output power, the multilayer stacks have to exhibit high magnetoresistive effects: giant magnetoresistance (GMR) or tunneling magnetoresistance (TMR). High spin polarization is a necessary condition for strong magnetoresistive and spin-transfer effects. Therefore, half-metals, which are metallic for one spin direction and semiconducting for the other, appear as the ideal choice. The combination of high magnetic anisotropy, large spin polarization and zero moment, was possible to realize in Mn_2Ru_xGa (MRG). Here, the first demonstration of successful integration of MRG in the perpendicular magnetic tunnel junction stack is presented. The magnitude of TMR obtained in the stacks where the MgO barrier was used, although high, can still be improved. The main reason for TMR ratios being lower than what theory predicts is the presence of impurities in the tunnel barrier. In order to enhance the device's performance, different insertion layers between MgO and MRG were incorporated. These layers are diffusion barriers which stop Mn diffusion into the tunnel barrier. The highest TMR to-date (40 % at 10 K) was achieved in MgO-based stacks where a layer of Al 0.6 nm is incorporated. Within this work it was demonstrated that the TMR is insensitive to the compensation of the ferromagnetic MRG electrode, thereby, highlighting the fundamental difference between an antiferromagnet and a compensated half-metallic ferrimagnet. The current work provides a detailed study of the annealing, the bias voltage applied across the tunnel barrier and the external temperature influence on the performance of MRG-based MTJs. This work contributes to the better understanding of spin transport in MRG-based MTJs and shows that these devices exhibit sufficient tunneling magnetoresistance ratios to observe current-induced magnetization dynamics, and, hence, establish a cornerstone of future spintronics devices.

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Magnetic order in neodymium metal – a new type of spin glass?

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Lanthanide metals can exhibit complex magnetic structures, e.g. helical/conical spin spirals or linear spin waves. Neodymium (Nd) shows the most complicated behavior exhibiting several magnetic phase transitions below it Néel temperature T_N = 19.9 K, resulting in multi-*q* order according to interpretations based on neutron diffraction experiments [1]. However, as these techniques lack spatial resolution, the variations in magnetic properties of Nd at the atomic length scale are unexplored. The local electronic structure of Nd(0001) surfaces has been studied only using spin-integrated STS [2,3].

I will present our most recent results of low-temperature (30 mK – 4 K) spin-polarized STM measurements of bulk-like Nd(0001) films grown on a W(110) substrate [4]. We observe multi-*q* magnetic behavior on the surface, as evidenced by strong short-range order, but without the existence of long-range order. Magnetic field and temperature-dependent measurements reveal high sensitivity of the spectral weight of *q*-states to applied fields, without any clear unique ground state, as well as evidence of so-called aging behavior in the magnetic state, which is a hallmark of spin-glass behavior. I will discuss our findings in the context of a new type of unconventional spin glass.

[1] R. M. Moon & R. M. Nicklow, J. Magn. Magn. Mater. 100, 139 (1991).
[2] D. Wegner et al., Phys. Rev. B 73, 165415 (2006).
[3] D. Wegner et al., Jpn. J. Appl. Phys. 45, 1941 (2006).
[4] U. Kamber et al., arXiv:1907.02295 (2019)

Modeling Skyrmion diffusion in thin film multilayers

Ulrich Nowak

University of Konstanz

Skyrmions are topologically protected quasi-particles that can appear in ferromagnetic thin-films multilayers and are increasingly discussed as possible building blocks for spintronic applications. Skyrmion diffusion [1] has been demonstrated in a recent combined experimental and theoretical study [2]. While being of fundamental interest as the type of diffusion yields information on transport and dissipation processes, thermally activated diffusion processes can also serve as a sensitive tool to analyze system properties.

We use the stochastic Landau-Lifshitz-Gilbert equation to simulate diffusive motion of Skyrmions in a PtIr/Fe-bilayer on a Pd surface. Here, the frustration of the isotropic exchange interactions in connection with the Dzyaloshinskii-Moriya interaction is responsible for the creation of skyrmionic structures with various topological charges [3]. We demonstrate the dependence of the diffusive motion on the topological properties and on the Gilbert damping parameter by calculating the diffusion coefficient for skyrmionic structures with different topological charges. Our simulations reveal that in this system skyrmionic structures are deformed by the Dzyaloshinskii-Moriya interaction rendering them elongated. This deformation leads to anisotropic diffusive behavior and rotational Brownian motion in a periodic potential, which in combination lead to a transition from anisotropic Brownian motion at short time scales to isotropic on longer time scales.

[1] Schütte et al., Phys. Rev. B **90**, 174434 (2014).
[2] Zázvorka et al., Nat. Nanotech. **14**, 658 (2019)
[3] Rózsa et al., Phys. Rev. B **95**, 094423 (2017)

Skyrmiogenesis: Skyrmion–antiskyrmion asymmetry from pair generation

Ulrike Ritzmann[1,2], Bertrand Dupé[3], Robert E. Camley[4], Joo-Von Kim[5]

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Topological non-collinear magnetic textures called skyrmions are the subject of intense research due to their stability and nontrivial dynamics. They represent key components for future technologies such as racetrack memories or bio-inspired computing devices. An important requirement is the controlled generation of skyrmions.

Here, we discuss how a skyrmion gas can be generated through the trochoidal motion of an initial antiskyrmion seed [1]. The dynamics is driven by current-induced spin-orbit torques, which deform the antiskyrmion core and leads to the emergence of the helicity as a dynamical variable. During trochoidal motion, a skyrmion–antiskyrmion pair is nucleated from the deformed core, much in the same way as a vortex–antivortex pair being nucleated prior to vortex core reversal. In contrast to the vortex core case, the skyrmion–antiskyrmion pair separates because skyrmions and antiskyrmions execute different motion under these torques. Skyrmions readily propagate away from the region of generation through linear motion, while the trochoidal motion of antiskyrmions mean they remain more localized to the generation region. Increased scattering between antiskyrmions leads to annihilation, which results in an overall excess of skyrmions in the system. We investigated how the generation rate and the skyrmion excess depend on the spin-orbit torque parameters. These results provide insight into how skyrmion ensembles may be created in realistic materials.

[1] U. Ritzmann et al., Nature Electronics 1, 451 (2018).

Magnetic MAX phases

Iuliia Novoselova[1], Andrejs Petruhins[2], Ulf Wiedwald[1], Johanna Rosen[2], Michael Farle[1] and Ruslan Salikhov[1,3]

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A new class of magnetic compounds, Mn-based MAX phases, was discovered in 2013 [1] and systematically extended to other compositions, for example, i-MAX phases [2]. In general, they are atomically layered carbides and nitrides with a unique combination of properties ranging from exceptional mechanical properties to self-healing and electrical conductivity. The talk is devoted to the existing stable MAX phases with long range magnetic order and its observed properties.

We performed a study exploring magnetic phase transitions, structural transformations, electrical transport and magnetic properties of the 100 nm thick MAX phase film Mn_2GaC grown on MgO (111). It has the highest magnetic ordering temperature of 507 K observed in magnetic MAX phases so far, and the spin structure is driven by competing ferromagnetic and antiferromagnetic interactions. We find the sign change of the large magnetostriction of 450 ppm being compressive (negative) at ambient temperature and tensile (positive) below 214 K. A sign reversal at the applied magnetic field is also observed in the magnetoresistance [3].

MAX phase films $(Cr_{0.5}Mn_{0.5})_2GaC$ on MgO (111) were studied in terms of the thickness dependence and long-term stability. 12.5 to 156 nm thick films were found to be phase pure with negligible *c*-axis lattice strain as a function of thickness. No significant influence of the interface layers on the magnetic characteristics under the investigation was observed. Samples with unprotected surface remained stable for more than one year at ambient conditions [4].

The financial support from DFG: SA 3095/2-1, DAAD: 57214224, KAW: 2015.0043 and SRC: 642-2013-8020 is gratefully acknowledged.

[1] A.S. Ingason, et al. Materials Research Letters 2, 89–93 (2014).
[2] Q. Tao, et al. Chemistry of Materials 31, 2476-2485 (2019).
[3] I.P. Novoselova, et al. Scientific Reports 8, 2637 (2018).
[4] I.P. Novoselova, et al. Materials Research Letters 7, 159-163 (2019).

Nanomagnonic properties of Biogenic magnetite

Benjamin W. Zingsem[1,2], Thomas Feggeler[1], Alexandra Terwey[1], Sara Ghaisari[3], Detlef Spoddig[1], Damien Faivre[3,4], Ralf Meckenstock[1], Michael Farle[1], Michael Winklhofer[1,5,6]

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[5]Institut für Biologie und Umweltwissenschaften, Carl von Ossietzky Universität Oldenburg, 26129 Oldenburg, Germany
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We report on the spectral properties of spin-waves (magnons) in individual chains of dipolar coupled magnetite nanoparticles. The particle-chains are biologically produced in magnetotactic bacteria. Straight chains where obtained from wild-type, curved and looped chains form mutant bacteria. A strong link between distinct spectral properties of the chains and their geometrical arrangement is identified, paving the way towards genetically engineered spin-wave computing. Each chain consists of ca. 12 nanoparticles with a diameter of about 30 nm, separated by a spacing of about 8 nm. Ferromagnetic resonance spectroscopy was employed to measure the magnonic Eigenstates of each particle in the chain as a function of the magnitude and direction of an applied magnetic field. The measurements are supplemented with micromagnetic simulations, which reveal the origins of spectral features such as band repulsion and attraction in the angular dependent spectral eigenstates. The emergent topology of the spin-wave band structure exhibits functional properties such as band deflection and band deformation, which may be harnessed in energy efficient magnon computing [1].

[1] B. Zingsem, T. Feggeler, et al., Nat. Commun. accepted (2019)

Spin-orbit technologies: from magnetic memory to terahertz generation

2019 IEEE Magnetics Distinguished Lecture

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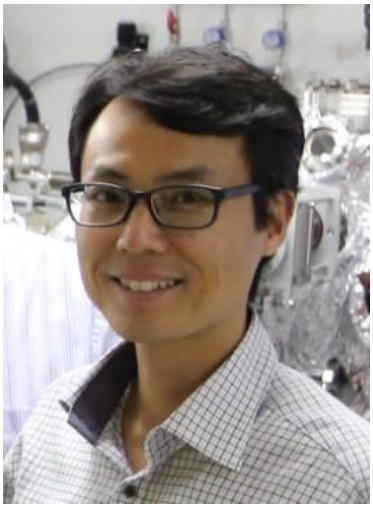

Spintronic devices utilize an electric current to alter the state of a magnetic material and thus find great applications in magnetic memory. Over the last decade, spintronic research has focused largely on techniques based on spin-orbit coupling, such as spin-orbit torques (SOTs), to alter the magnetic state. The phenomenon of spin-orbit coupling in magnetic heterostructures was also recently used to generate terahertz emission and thus bridge the gap between spintronics and optoelectronics research.

I will introduce the basic concepts of SOTs, such as their physical origin, the effect of SOTs on a magnetic material, and how to quantitatively measure this effect [1,2]. Next, I will discuss the latest trends in SOT research, such as the exploration of novel material systems like topological insulators and two-dimensional materials to improve the operation efficiency [2,3]. Following this, some of the technical challenges in SOT-based magnetic memory will be highlighted [3]. Moving forward, I will introduce the process of terahertz generation in magnetic heterostructures [4], where the spin-orbit coupling phenomenon plays a dominant role. I will discuss the details of how this terahertz emission process can be extended to novel material systems such as ferrimagnets [5], topological materials [6], and 2D materials [7]. The final section will focus on how the terahertz generation process can be used to measure SOTs in magnetic heterostructures, thus highlighting the interrelation between terahertz generation and the SOTs, which are linked by the underlying spin-orbit coupling.

[1] X. Qiu et al., "Characterization and manipulation of spin orbit torque in magnetic heterostructures" Adv. Mater., 30, 1705699 (2018).

[2] Y. Wang et al., "FMR-related phenomena in spintronic devices" J. Phys. D: Appl. Phys., 51, 273002 (2018).

[3] R. Ramaswamy et al., "Recent advances in spin-orbit torques: Moving towards device applications" Appl. Phys. Rev., 5, 031107 (2018).

[4] Y. Wu et al., "High-performance THz emitters based on ferromagnetic/nonmagnetic heterostructures" Adv. Mater., 29, 1603031 (2017).

[5] M. Chen, et al., "Terahertz emission from compensated magnetic heterostructures," Adv. Opt. Mater., 6, 1800430 (2018).

[6] X. Wang, et al., "Ultrafast spin-to-charge conversion at the surface of topological insulator thin films" Adv. Mater. 30, 1802356 (2018).

[7] L. Cheng, et al., "Far out-of-equilibrium spin populations trigger giant spin injection into atomically thin MoS2" Nat. Phys. 15, 347 (2019)

Biography

Hyunsoo Yang obtained the bachelor's degree from Seoul National University. He worked at C&S Technology, Seoul, Korea; LG Electronics, San Jose, Calif.; and Intelligent Fiber Optic Systems, Sunnyvale, Calif. In 2006, he received the doctorate from Stanford University, where he worked on optoelectronic devices. From 2004 to 2007, he was at the IBM-Stanford Spintronic Science and Applications Center. He is currently a GlobalFoundries chaired associate professor in the Department of Electrical and Computer Engineering, National University of Singapore, working on various magnetic materials and devices for spintronics applications. He has authored 170 journal articles, given 100 invited presentations, and holds 15 patents. He won the Outstanding Dissertation Award for 2006 from the American Physical Society's Topical Group on Magnetism and Its Applications.

Spin-to-charge current interconversion by Edelstein effect in 2D electron systems using FMR spin pumping method

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Several non-magnetic materials, ranging from bulk materials to 2D electron gas (2DEG) at Rashba interfaces or topological insulator (TI) surfaces, have recently been shown to allow the transformation of charge currents into pure spin currents. The discovery of this property is the basis of a new research topic, spinorbitronics, which aims particularly at understanding how spin-orbit interaction can be used to control magnetization. The manipulation of those pure spin currents, which correspond to a flow of angular momentum without net charge flow, can be used to induce magnetic precession or magnetization switching. This allows foreseeing numbers of spintronics memory and logic applications, and opens new fundamental challenges for the condensed-matter community. My presentation will focus on a method for studying the spin to charge conversion, named spin pumping. The principle is to use ferromagnetic material deposited on top of a spin-orbit material. When exciting the ferromagnet at the ferromagnetic resonance, the magnetization precession in the ferromagnet injects a pure spin current into the spin-orbit material. The injected spin current is then converted into a transverse charge current, via Inverse Spin Hall Effect in heavy metals/ alloys [1], or via Inverse Edelstein Effect at Rashba interfaces [2] or topological insulator surfaces [3]. I will show that we could obtain highly efficient spin-to-charge conversions by using the 2DEG in STO/LAO Rashba interface [4] and topological insulators [5, 6], which are higher than using metallic alloy spin Hall effect materials [1, 7] and pure elements like Pt [8].

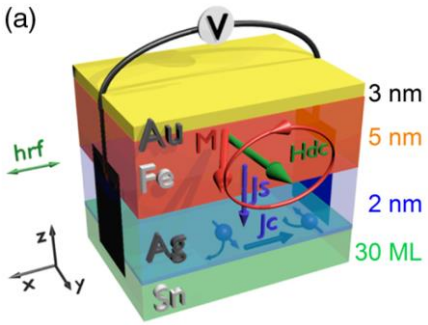

Fig. 1: Experimental setup for spin pumping into α-Sn by ferromagnetic resonance (FMR) of a Fe layer (from Ref. 5).

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Spin textures and spin waves as seen by x-ray microscopy

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The investigation of spin-wave phenomena, also referred to as *magnonics*, plays an important role in present condensed matter research [1] [Fig. 1]. This holds true, in particular, as spin waves are seen as signal carriers for future spintronic information processing devices, with a high potential to outperform present charge-based technologies in terms of energy efficiency and device miniaturization. Yet a successful implementation of magnonic technology will require the usage and control of spin waves with nanoscale wavelengths.

Here, I will show that ferromagnetic spin textures in metallic systems can be used as nanoscale spin-wave emitters and wave guides. In particular, topological spin vortex cores prove to act as efficient and tunable generators for sub-100 nm waves [2,3] [Fig. 2(a,b)], while domain walls can be utilized as quasi one-dimensional channels for spin-wave propagation and routing [4] [Fig. 2(c)]. The underlying spin dynamic processes were directly imaged by using time-resolved x-ray microscopy.

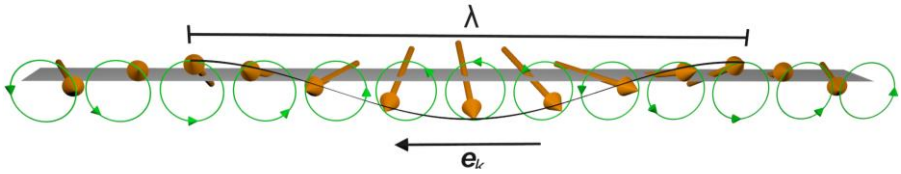

Figure 1: Schematics of a propagating spin wave [3].

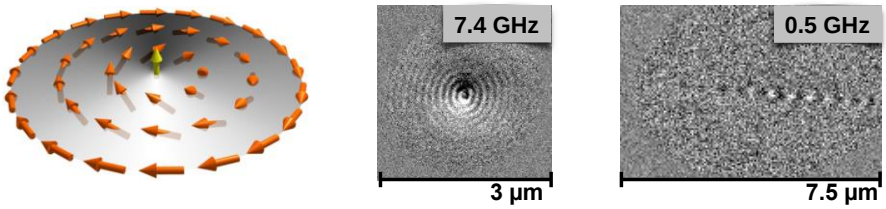

Figure 2: (a) Schematics of a spin vortex. (b) Spin-wave emission from a vortex core. (c) Domain wall as 1D spin-wave channel.

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Ultrafast dynamics at optically-excited magnetic meta-surfaces

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Interaction of femtosecond (fs) laser pulses with magnetic materials result in an immense variety of physical phenomena from different area of physics: nonlinear optics, ultrafast spintronics, acoustics, physics of shock waves and/or laser-induced phase transitions. From a metrological perspective, different time scales associated with those phenomena can be measured with fs temporal resolution in a variety of conventional linear and nonlinear optical pump-probe experiments. However, absorption of fs laser pulse by an opaque magnetic material may trigger different coherent and incoherent processes involving simultaneously electrons, phonons, and magnons, thereby rendering identification of the underlying mechanisms extremely challenging.

Complexity of the interpretation of ultrafast optical measurements can be reduced by the investigation of the experimentally accessible monochromatic excitations and their interactions: periodic oscillations of electromagnetic fields at the (fundamental, second harmonic, third harmonic etc.) optical frequencies, elastic deformations at MHz-THz frequencies and perturbations of the magnetic order like the ferromagnetic resonance (FMR) or exchange-coupled magnon modes oscillating at GHz-THz frequencies.

Monochromatic acoustic waves can be generated by fs laser excitation of periodic gratings, either in the so-called transient grating geometry [1-2] or using permanent gratings [3]. Characteristic feature in these experiments is the possibility to excite monochromatic surface acoustic waves (SAWs) with frequencies tunable by the grating periodicity up to a few tens of GHz in the case of sub-wavelength periodic structures (100 nm). Such sub-wavelength spatial periodicity represents the link between ultrafast magneto-acoustics and (magneto-)optics of meta-surfaces. Proper combination of the grating periodicity and the magnitude of an external magnetic field may fulfill the resonance conditions for the FMR frequency with SAWs and result in the resonant enhancement of the FMR precession [1-3], with the onset of parametric instabilities [2]. Whereas excitation of large-amplitude FMR precession through the laser-mediated resonant magneto-elastic interactions have not yet been optimized, such possibility would open a new avenue to modulate optical properties of magnetic meta-surfaces. Since static nonlinear magneto-optical and/or magneto-plasmonic effects are giant as compared to the linear ones [4-7], it is better to go beyond linear magneto-optical techniques and probe dynamics of the resonant magneto-acoustic interactions [1-3] using nonlinear magneto-optical detection schemes [4-7]. It can help to develop real-life applications with magnetic meta-surfaces modulated on ultrafast time scales.

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Tunable ferromagnetic resonance in coupled trilayers with crossed in-plane and perpendicular magnetic anisotropies

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Thin films with weak perpendicular magnetic anisotropy (PMA) exhibit stripe domains, which could be used to control reconfigurable magnonic devices [1]. To further increase the versatility of PMA-based material systems, the effect of controllably coupling a 64 nm thick, hard magnetic $NdCo_x$ film with PMA to a 10 nm thick, soft magnetic $Ni_{80}Fe_{20}$ film with in-plane magnetic anisotropy (IMA) through a non-magnetic Al spacer is investigated [2]. Using the transverse magneto-optical Kerr effect, alternating gradient force magnetometry as well as broadband vector network analyzer ferromagnetic resonance (VNA-FMR) spectroscopy, the influence of both Co concentration (X = 5;6;7:5; 9) and Al spacer thickness (T = 0 nm, 1.5 nm, 2.5 nm, 5 nm, 10 nm, 20 nm) on the static and dynamic magnetic properties, respectively, of coupled bi- and trilayers is studied. The proximity to the hard $NdCo_x$ layer modifies the magnetic properties of the soft Py film, resulting in both an induced stripe domain pattern and a transfer of rotatable anisotropy.

Two of the most striking effects of the coupling between the IMA and PMA layers can be observed in the in-plane VNA-FMR spectra of the trilayer samples. First, compared to a single Py film, there is a significant increase in the zero-field FMR frequency from 2.0 GHz up to 6.4 GHz, whose exact value can be pre-defined by choosing a certain combination of Co concentration and Al spacer thickness. Second, there is a frequency hysteresis in the stripe domain state, which allows the FMR frequency of the Py layer to be tuned as a function of the magnetic history, leading to a reconfigurable functionality. The maximum difference between the frequency branches for increasing and decreasing field is as high as 1 GHz, corresponding a tunability of about 20% at fields of typically less than 0.1 T. Though the frequency hysteresis can be observed both when the bias field is applied along easy axis or hard axis, respectively, it is generally much more pronounced in the latter case. Among the other notable features within the hysteretic part of the in-plane VNA-FMR spectra are frequency jumps, local frequency maxima, as well as significant changes in both mode intensity and linewidth. From a full set of VNA-FMR measurements (in-plane, out-of-plane, azimuthal, polar), the relevant magnetic anisotropies have been determined and the role of the IMA, that together with its relative orientation with respect to the in-plane bias field is believed to be at the origin of the observed dynamic properties, is discussed.

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Magnetic relaxation in ferromagnetic metallic films with enhanced perpendicular anisotropy

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Magnetic relaxation describes the time evolution of a magnetic system after external excitations, such as an applied magnetic field, microwaves, electrical and laser pulses, etc. The characteristic rate at which magnetic systems reach their equilibrium state is known as the relaxation rate. Spintronic and magnonic elements (which are suitable for nonvolatile and energy consuming logics and data processing technologies) require metallic ferromagnets with low magnetic relaxation rates and high perpendicular anisotropy. Perpendicular anisotropy can be induced by interfacing ferromagnetic films with normal metals, such as Pt or Pd. However, such an interface leads to an increased magnetic damping due to the significant spin pumping contribution [1]. We use alternative approaches to induce perpendicular magnetic anisotropy in Fe-Co and Fe-Ni films, and study their influence on magnetic relaxation parameters using ferromagnetic resonance (FMR).

Large perpendicular anisotropy energy density of 0.42 MJ/m^3 was achieved in 20 nm $(Fe_{0.4}Co_{0.6})_{0.96}B_{0.04}$ epitaxial films due to Fe-Co lattice strain induced by interstitial B. Comparison of the magnetic damping parameter with the damping parameter in the reference $Fe_{0.4}Co_{0.6}$ film revealed a 30% reduction, indicating that the magnetization relaxation in the strained sample is slower [2].

The enhancement of perpendicular anisotropy in Fe-Ni films was achieved by the doping with 5 – 13 at.% Gd [3]. FMR studies revealed a noticeable increase of the damping, it being almost twice as large in 13 at.% doped sample as compared to the reference $Fe_{0.19}Ni_{0.81}$ sample. However, time-resolved pump-probe measurements at low magnetic fields revealed that the relaxation rates in the doped sample are almost twice as small [4].

Both studies show the opportunity to increase perpendicular anisotropy and decrease relaxation rate simultaneously. The reasons of this counterintuitive behavior of the magnetic relaxation in Fe-Co and Fe-Ni films will be explained. The comparative analysis of field and time domain FMR methods used to investigate the magnetic damping in Fe-Ni-Gd films will be discussed. Additional information on relaxation in high-frequency spin wave modes will be presented.

We are thankful to all collaborators participating in this research, whose names appear in the references below.

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Tuning magnetic anisotropy in nanostructures for biomedical applications

2019 IEEE Magnetics Distinguished Lecture

Hari Srikanth

University of South Florida, USA

Magnetic nanoparticles have been building blocks in applications ranging from high density recording to spintronics and nanomedicine [1]. Magnetic anisotropies in nanoparticles arising from surfaces, shapes and interfaces in hybrid structures are important in determining the functional response in various applications. In this talk I will first introduce the basic aspects of anisotropy, how to tune it in nanostructures and ways to measure it. I will discuss resonant RF transverse susceptibility, that we have used extensively, as a powerful method to probe the effective anisotropy in magnetic materials. Tuning anisotropy has a direct impact on the performance of functional magnetic nanoparticles in biomedical applications such as contrast enhancement in MRI and magnetic hyperthermia cancer therapy. There is a need to improve the specific absorption rate (SAR) or heating efficiency of nanoparticles for hyperthermia and I will focus on the role of tuning surface and interfacial anisotropy with a goal to enhance SAR. Strategies going beyond simple spherical structures such as exchange coupled core-shell nanoparticles, nanowire, nanotube geometries can be exploited to increase saturation magnetization, effective anisotropy and heating efficiency in magnetic hyperthermia [2,3]. This lecture will combine insights into fundamental physics of magnetic nanostructures along with recent research advances in their application in nanomedicine [4].

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Biography

Hari Srikanth is a Professor of Physics at the University of South Florida in Tampa, FL. He received his Ph.D. in experimental condensed matter physics from the Indian Institute of Science. After postdoctoral research for several years, Hari joined USF in 2000 and established the Functional Materials Laboratory. His research spans a wide range of topics including magnetization dynamics in nanostructures, applications of magnetic nanoparticles in nanomedicine and RF devices, magnetic refrigerant materials, spin calorics, microwave materials and complex oxides with competing magnetic phases. He has over 250 publications and has given over 200 invited talks around the world. Hari has developed a short tutorial on nanomagnetism, enjoys delivering pedagogical lectures for a broad audience and especially interacting with students and early career researchers. Hari is a *Fellow of the American Physical Society*, with the citation mentioning his contributions in the field of nanomagnetism, and a *Senior Member of IEEE*. He is currently an Associate Editor for *Journal of Applied Physics*. Hari has been closely involved with the MMM and INTERMAG conferences for more than 15 years serving as Publication Editor, Publication Chair and on program committees. He is also a 2019 Fulbright awardee. Hari has been a short term visiting professor in Slovak Academy of Sciences (Kosice), Basque Center for Materials (Bilbao), Indian Institute of Technology (Bombay), Indian Institute of Science (Bangalore), Federal University of Rio de Janeiro (Brazil) and Immanuel Kant Baltic Federal University (Kaliningrad).

Study of interacting assemblies of nanomagnets: competing effects

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A general formalism is built to simultaneously account for intrinic features and collective behavior of assemblies of nanomagnets and to study their competition. We have used this formalism to compute physical observables such as the (quasi-)equilibrium magnetization, AC/DC susceptibility, FMR spectrum, relaxation rates, and the specific absorption rate [1-7]. In some favorable situations, we obtain relatively simple analytical expressions that help better understand the underlying physics and the related competing effects. By way of illustration, in this talk we first discuss a few examples of experimentally realizable situations in which surface effects may "screen out" the dipolar interactions in an assembly of nanomagnets, which then would behave as a noninteracting system [8]. A second topic we intend to discuss will be the relaxation rate, and thereby the blocking temperature, of a chain of dipolar-coupled nanomagnets [9].

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Magnetic relaxation dynamics in soft matter nanoparticle composite systems

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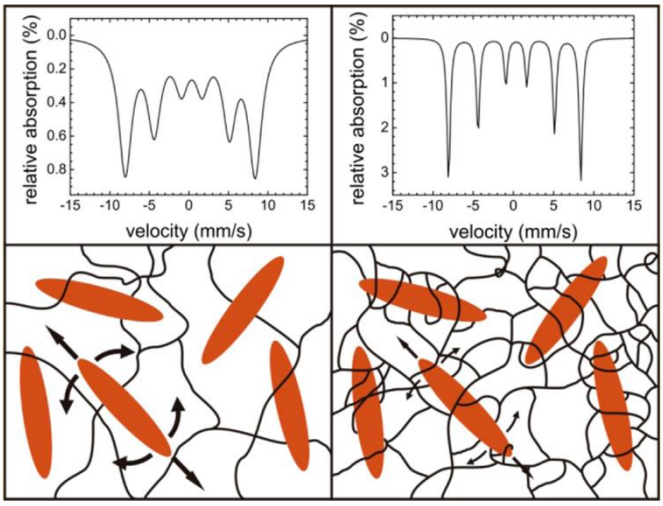
Although composite materials made of magnetic nanoparticles and hydrogels have been of great interest in the last years, it has not been fully understood, to which degree the free motion of the nanoparticles is constrained. Many of the most often used techniques are sensitive to the macroscopic magnetic moments, while the movements of individual particles cannot be determined. Therefore, a joint approach of Mössbauer spectroscopy, measuring the diffusive motion of iron ions on the atomic level [1], and AC-susceptometry is a promising combination to provide new information.

In this work the constrained motion of spindle-shaped hematite nanoparticles of about 400 nm in PAAm-hydrogels with different degrees of crosslink density is measured utilizing the line broadening observable in Mössbauer spectra (see schematic figure) at 265−293 K [2]. A slight decrease of nanoparticle mobility is observed upon increasing cross-link density. Mössbauer spectra of the same nanoparticles in 60 wt % sucrose solution, used as reference material, display line broadening of the same magnitude as the hydrogel samples, indicating a similar degree of motion at the atomic scale and the time scale of the Mössbauer experiment. AC (alternating current) susceptibility data indicate that the magnetic relaxation of the nanoparticles in sucrose solution mainly occurs by Brownian motion, while the absence of magnetic loss within the investigated frequency range observed in measurements on hydrogel samples reveals very limited particle mobility. This apparent contradiction between results on particle dynamics in hydrogels by Mössbauer spectroscopy and AC susceptibility measurements is explained in terms of constrained particle mobility at atomic scales [2].



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Magneto-optical Activity of Cobalt Ferrite Nanoparticles confined in Silica Capsules and modified by One Single Gold Nanoparticle

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The rotation of the polarization of light in a magnetized medium can be observed either in reflection (Kerr rotation) or in transmission (Faraday rotation) [1]. These magneto-optical (MO) effects are typically small in most media, and consequently, different ways to modify or even enhance them have been reported. One way to do that, takes into account the integration of optical resonances of noble metal nanostructures [2].

Herein, we demonstrate a modified optical Faraday rotation in a unique composite nanostructure made of cobalt ferrite nanoparticles trapped in a silica capsule, employing the optical resonance of just one single noble metal (Au) nanoparticle [3].

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EXAFS characterization of magnetic nanostructures

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Among the characterization techniques, X-ray Absorption Spectroscopy is an effective tool to probe the chemical environment around an absorber element and get information on the chemical and structural features of the materials. In this talk, some example of Extended X-ray Absorption Fine Structure (EXAFS) study will be reported with the aim of highlighting the role of the chemical and structural properties on the magnetic behavior of different magnetic nanoparticles, nanocomposites and thin films. In particular, EXAFS characterization played an important role in revealing the nature of the magnetic interactions within a system of ferromagnetic nanoparticles (Co, Fe) dispersed in an antiferromagnetic matrix (Mn, Cr) [1-3] or in correlating the magnetic anisotropy and the chemical order in FePt thin films doped with a third element (Cu, Tb) [4, 5]. Moreover, in-situ EXAFS study has been recently applied to study the reduction of $Fe(H_2O)_6PtCl_6$ crystalline precursor salts allowing highly-ordered L10 - FePt nanoparticles to be synthesized [6]. Due to its peculiar characteristics, i.e. selectivity and high sensitivity, Extended X-ray Absorption Fine Structure analysis represents the main technique to investigate the local properties in many systems whose behavior is strongly affected by the atomic arrangement, showing a great versatility in characterizing a variety of magnetic systems under different experimental conditions.

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Specific properties of FePt nanoparticles and self-organization on graphene

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The FePt alloy, when chemically ordered in the $L1_0$ phase [1], is among the magnetic materials displaying the highest magnetic anisotropy constant. Therefore it is a perfect candidate for ultra-high density magnetic storage applications, provided nanoparticles can be prepared in such a high anisotropy phase and organized in a 2D array. One path of bottom-up elaboration following a physical route consists in using template surfaces with specific sites regularly distributed. Such a 2D lattice can be obtained with the moiré (hexagonal lattice of 2.5 nm cell parameter) displayed by a graphene layer epitaxially grown on a Ir(111) surface [2]. In this presentation I will discuss the specificities of small FePt nanoparticles [1,3] (structure and magnetic properties) and show how they can self-organize on a graphene moiré pattern.

The organization of FePt nanoparticles, prepared using Low Energy Cluster Beam Deposition [4] of preformed size-selected particles (around 2 nm diameter), has been determined by grazing incidence x-ray scattering measurements [5,6]. We find that particles occupy specific sites of the moiré lattice, what can be preserved up to temperatures around 700°C. Using X-ray Magnetic Circular Dichroism measurements, we can see a clear evolution of the magnetic properties of the FePt nanoparticles induced by annealing (anisotropy modification, interface effects between FePt and the graphene...), while the particles keep their individuality [6].

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Engineering Thermal Relaxation Pathways for Nanomagnetic Computation

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Nanomagnetic logic, which uses arrays of magnetostatically-coupled single-domain nanomagnets for computation, is a low-power alternative to current charge-based computation in semiconductor devices and furthermore allows for integration of memory and information processing within the same architecture [1]. At the heart of the computation process lies the thermal relaxation from a field-set state towards a low-energy state of the interacting ensemble. In this talk, I will explore two recent concepts for the control of thermal relaxation pathways in nanomagnetic circuits:

First, the single-spin-flip connectivity of magnetic states, whose energies depend on the spatial arrangement of the nanomagnets, may lead to pathways of different kinetic character, which we termed monotonic and intermittent. These lend themselves to the implementation of deterministic and probabilistic computation, respectively [2].

Second, by adapting ideas from the emerging field of thermoplasmonics [3], an alternative to slow global heating of nanoscale magnets via contact to a heat reservoir has recently been demonstrated by combining gold nanoantennas with magnetic elements: Plasmon-assisted photoheating of such hybrid structures allows for temperature increases of up to several hundred Kelvins within time scales as short as a few tens of picoseconds. In addition, spatially-selective and sublattice-specific heating can be achieved by controlling the focal position and light polarisation of the laser beam [4].

Combining these two concepts, I explore the flexibility of fast, spatially-, and element-selective magnetic thermalization for the kinetic control of relaxation pathways for nanomagnetic computation.

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[3] *Thermo-Plasmonics: Using Metallic Nanostructures as Nano-Sources of Heat*; G. Baffou and R. Quidant; Laser Photonics Review **7**, 171 (2013).

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Hollow Core Dendrimers: Theory, Simulations, and NMR Experiments

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Since the pioneering works on dendrimer synthesis the question about the existence of a free space (hollow core or cavity) within dendrimers and the possibility of its use for practical purposes plays an important role. Theoretical and experimental studies of this problem have a long history; at the same time there is still no systematic exposition of the results of researches on this topic in the literature. The first part of this report is devoted to a detailed discussion of the dendrimers' structure and a critical analysis of the current state of the theory and existing experimental data for homopolymeric dendrimers in dilute solution.

In the rest part of the report the studies of copolymeric dendrimers, in which the end segments have different physico-chemical properties than the inner ones, are considered. It is found that the incompatibility between the terminal and the inner segments is the main factor favoring formation of a "hollow" interior in the dendrimer in dilute solution [1]. It is shown that the solvent quality with respect to terminal groups plays an important additional role.

Obtained results allow us to explain molecular dynamics simulation results [2] and NMR experimental data [3] for G=4 generation carbosilane dendrimer with terminal cyanobiphenyl groups in dilute chloroform solution. In this copolymer dendrimer the "hollow" interior is formed with decreasing temperature which corresponds to increasing segregation effect.

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Application of magnetic nanoparticles in cancer theranostics

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Magnetic nanoparticles (MNP) are in the field of great interest in two past decades. MNP can be used as an effective MRI contrast agent, drug delivery systems and effective formulations for magnetic hyperthermia. Such variety of application in each particular case can be reached only by specific chemical design of magnetic core structure and surface coating. Thus optimization of such parameters allows using these nanoparticles not only in separate application, but also in combined modalities.

For combined drug delivery and MRI imaging we have developed complex system based on iron oxide nanocrystals, coated with human serum albumin (HSA-MNP) with following crosslinking with formation of stable biocompatible shell. Physicochemical properties of HSA-MNP were investigated in details by HAADF-TEM, DLS, AFM, also magnetization and T2 relaxation properties were investigated. HSA serves as a natural transport protein for xenobiotics in blood and can effectively bind drug molecules to surface. Our experiments have shown that HSA-MNP were able to bind doxorubucin, cisplatin and bacteriochlorine *a* molecules, effectively delivery this drugs to tumor cells and tissue. Particularly for doxorubicin loaded nanoparticles we have shown effective imaging of 4T1 mouse breast cancer model accompanied with increase of median survival from 26 to 39 days.

Bacteriochlorine *a* is a heteromacrocyclic organic molecule which can act as photosensitizer (PS). Under light irradiation PS molecules promotes formation of reactive oxygen species (ROS) which damage cell compartments and lead to cell death. However low solubility in water restricts application of these molecules without further modification. To overcome this disadvantage we have developed a method for loading of PS on HSA-MNP surface. PS loaded HSA-MNP has shown similar photoinduced cytotoxicity in comparison with free drug and were stable in water solution for few weeks. Moreover *in vivo* experiments with mice bearing tumors have shown that after *i.v.* injection of PS loaded HSA-MNP we were able to detect PS delivery to tumor by both MRI and *in vivo* fluorescence.

This results allow to propose HSA coated MNP as a perspective tool for drug delivery of different antitumor drugs for cancer treatment.

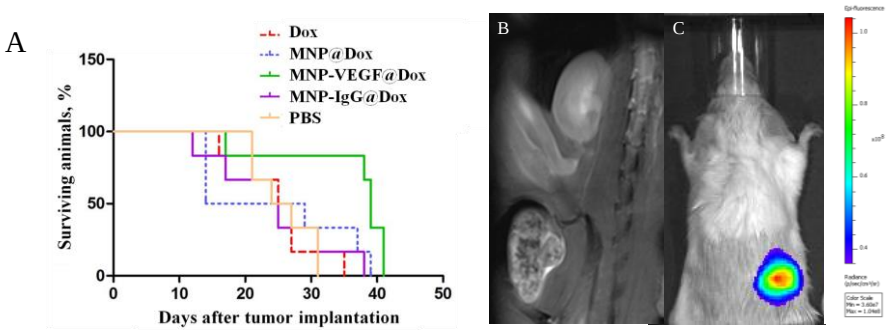

Fig. 1. Survival curves of animals bearing experimental 4T1 tumors treated with Dox, PBS and different types of Dox-loaded magnetic nanoparticles (A). Representative MRI (B) and fluorescent imaging (C) of 4T1 tumor bearing mice 6h after *i.v.* injection of PS loaded HSA-MNP.

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Aggregates and dipolar interactions in nanoparticle assemblies for hyperthermia

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Magnetic hyperthermia is one of the most promising biomedical applications of magnetic nanoparticles (NP) and is intended to be alternative to cancer therapies based on drug delivery and radiotherapy. It is based on the fact that magnetic NP dissipate heat when an oscillating magnetic field is applied to them in a quantity (specific absorption rate, SAR) that is closely related to the area of the hysteresis loop. The main problem in the field has become to find the suitable range of parameters that maximize SAR for a given material [1], SAR depends of course on the amplitude of the applied magnetic field and its frequency, but also on intrinsic parameters of the NP such as saturation magnetization, anisotropy, shape and size [2]. Although the role of external parameters is somehow well contrasted, there is still ongoing controversy on the role that dipolar interactions (DI) and aggregation state of the assemblies play on SAR. We will present results of Monte Carlo simulations of hysteresis loops of interacting NP assemblies in the macrospin approximation [3]. We will present first results of different regular spatial arrangements of NP, showing the influence of interparticle separation and particle size on SAR. Next, we will study the case of randomly placed NP with varying concentrations mimicking experimentally found situations [4] (inside and at the surface of liposomes/cells, clusters). It is found that formation of chain-like arrangements or assemblies with prolate shapes, lead to considerable increases in SAR due to DI.

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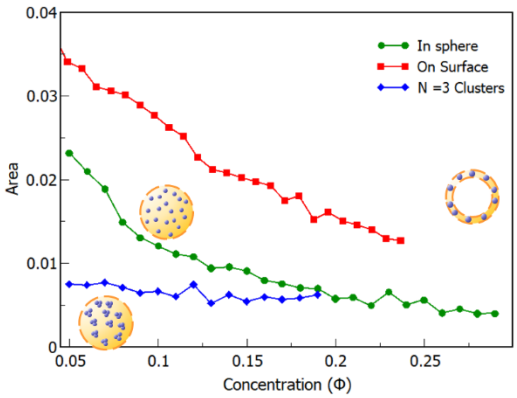

Concentration dependence of the hysteresis loop area for different kinds of NP random assemblies.

Magnetic Particle Hyperthermia: Current trends and prospects

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Magnetic nanoparticles (MNPs) of different phases, sizes and shapes are currently studied as enhanced performance magnetic particle hyperthermia (MPH) agents due to their magnetic features, affected by individual particles' intrinsic features and collective phenomena where particles as parts of an ensemble, within a colloidal suspension, interact with each other. Different formations of particles include single-phase particles such as Fe_3O_4 or other ferrite types. Nanoparticles will eventually appear with suppressed magnetic features, depending on surrounding conditions/features/interactions, thus their configuration in 2D or even 3D oriented assemblies may provide a powerful pathway to control their macroscopic magnetic response on demand. Such assemblies have a direct impact on effective anisotropy, susceptibility and hysteresis losses. The choice of the MNPs to be employed not only as hyperthermia agents but more generally as biomedical probes has to do with four aspects: a) material b) size, c) shape and d) formation (i.e. core-shell, multi-core, chains). Since an external magnetic field is the drive of MNPs, we should have to maximize field effect by tuning MNPs collective magnetic features. Magnetism both at the nanoscale level (single particles) but also macroscopic collective magnetic features (ensembles) will be dramatically different for the different formations while their collective magnetic features are visualized in magnetic hysteresis loops.

Current trends of magnetic particle hyperthermia include among others:

Self-regulated hyperthermia: Magnetic nanoparticles possessing low Curie temperatures (T_C) offer the possibility for self-regulated heating of cancer cells, where the T_C acts as an upper limit to heating to prevent damage to neighboring healthy tissues. Once they reach the Curie temperature, M_s drops to zero and heating stops. Thus, if the Curie temperature is fixed by judicious selection of particle composition and size, hyperthermia response is eventually fixed below a certain temperature level preventing excessive temperatures.

Focused-hyperthermia: A typical problem of the application of hyperthermia is the difficulty to locate the heat without damaging potentially healthy surrounding tissues. The control of temperature rise in magnetic particle hyperthermia may be achieved by the incorporation of an external DC magnetic field concurrently with the AC field. The combination of AC and DC fields may be a feasible method not only to optimize and regionally focus magnetic particle hyperthermia effect to specific malignant sites, but to combine two magnetic particle modalities such as magnetic particle hyperthermia and magnetic particle imaging. (*Figure 1*).

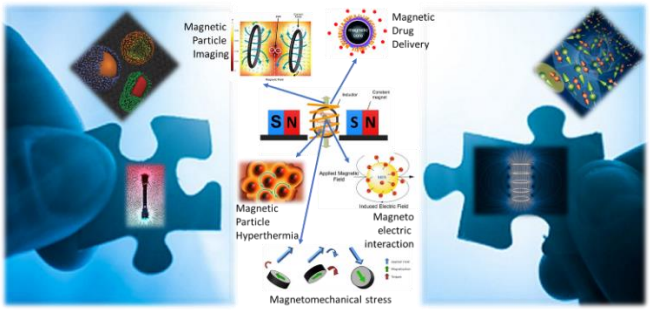

Figure 1: Concurrent application of AC and DC magnetic fields manages to a) focus magnetic particle hyperthermia effect b) induce enhanced magnetomechanical stresses c) originate tunable electric signals via magnetoelectric interactions. Additionally, magnetic particle imaging and magnetic drug delivery perspectives are foreseen with proper functionalization schemes.

Multifunctionality-Combinatory schemes: The simultaneous drug-release during MPH is an issue under study. Attachment of drug via heat-breaking bonds with MNPs or encapsulation of drugs within temperature-sensitive structures renders MPH not only as heating modality for cancer treatment but also as trigger to ignite drug delivery upon request.

Synthesis and Characterization of Carbon Coated Fe-Fe_3C "Core-Shell" Nanoparticles for Magnetic Hyperthermia

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Particularly intense and continuously growing interest to the fabrication of core-shell nanoparticles been recorded in recent years. It is relevant to unique achieved sizes and corresponding unusual properties of synthesized nanoparticles.

The carbon-encapsulated iron-cementite (Fe-Fe_3C) nanoparticles synthesized by a single-step solid-state pyrolysis of iron phthalocyanine are promising nanomaterials for medicine due to their valuable magnetic and structural properties. To obtain required magnetic characteristics of such nanoparticles controllable by pyrolysis conditions one needs reliable structural information of the atomic architecture of the obtained nanoparticles in (Fe-Fe_3C) composition with Fe atoms having different local surroundings. The latter factor complicates the structural characterization of sample. Therefore, complementary measurements are necessary using the TEM, SAXS, XRD, XANES and EXAFS, including results of simulations by the method of reactive force field molecular dynamics (ReaxFF MD). These simulations enabled to reveal the most plausible combinations of the local structures of Fe-atoms in (Fe-Fe_3C) nanoparticle, which results in the difference of corresponding atomic pair radial distribution functions relatively to iron (RDF) by further subtraction by the comparison with experimentally obtained RDF for iron atoms in the studied sample.

The magnetization curves of (Fe-Fe_3C) "core-shell" nanoparticles display sharp demagnetization jumps at low fields associated with a sudden enhancement of shell moment. The TEM image and hysteresis loop are shown in Fig.1.

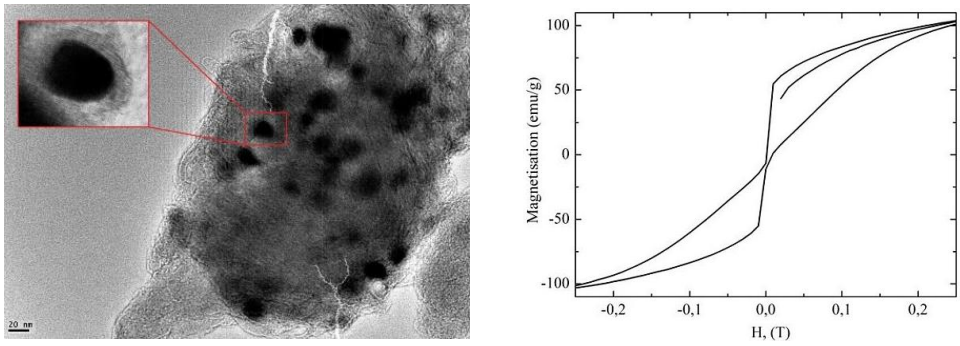

Fig.1. TEM image and hysteresis loop of (Fe-Fe_3C)@C nanocomposites.

This work was supported by the RA MES State Committee of Science and Russian Foundation for Basic Research in the frames of the joint research projects SCS 18RF-120 and RFBR 18-52-05004 respectively. This work at CSULA supported by the CREST program and NSF-Partnerships for Research and Education in Materials under Grant DMR-1523588.

Posters

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Tunable saturation magnetization and low Gilbert damping of ion-irradiated FeRh thin films
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Internal stresses influence on functional properties of Heusler-type microwires
Sergey Shevyrtalov, Valentina Zhukova, Arcady Zhukov

Magnetic properties of high entropy CoCrFeMnNi alloy prepared by high energy ball milling
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Hot carrier effects in graphene THz magneto plasmons
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Paramagnetic molecules on Fe_3O_4 – Au nanoparticles as a spin-current detector
T. Strusch, R. Meckenstock, Y. Nalench, M. Abakumov, M. Farle, U. Wiedwald

Comparative study of magnetic stability of Fe on GaAs (100) and GaAs (110) using in-situ FMR

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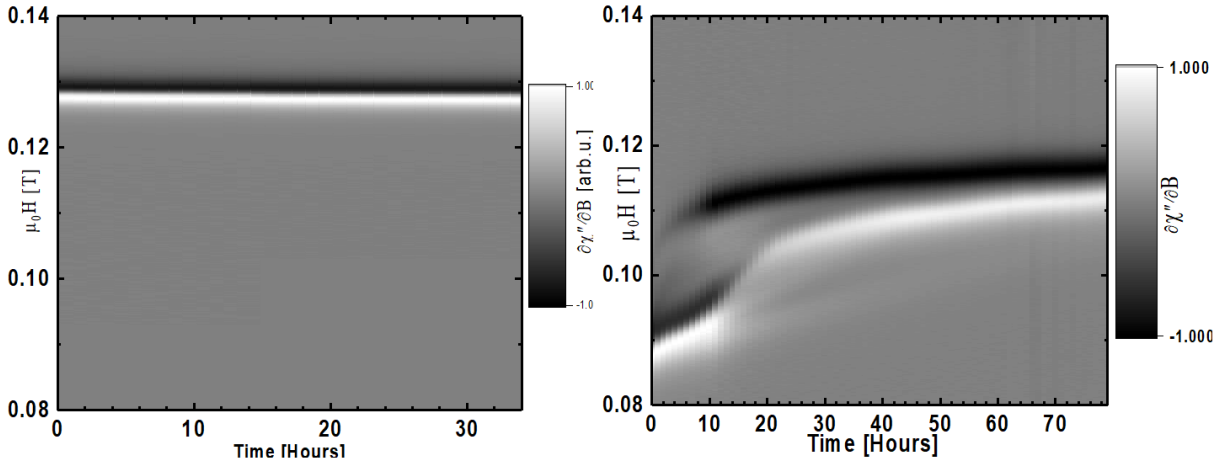
Ferromagnetic Resonance (FMR) is a powerful tool used for examining magnetic anisotropy, g-factor and intrinsic and extrinsic damping parameter of materials. Fe on GaAs is considered as a good candidate for spintronics application as Fe has high Curie temperature and exhibits high spin polarization, larger than Fe_3Si at room temperature. This system has been extensively studied for its structural and magnetic properties, however some evidences are still lacking.

We studied the time dependent evolution of magnetization dynamics using in-situ FMR under ultra-high vacuum (UHV) conditions to verify the stability of uncapped 4 nm (~20 monolayers) Fe film epitaxially grown on GaAs (100) and (110) substrates. We found that Fe on GaAs (100) is characterized by uniform growth with stable static and dynamic magnetic conditions over more than 35 hours after deposition while all magnetic properties of Fe on GaAs (110) change with time which is most probably due to island like growth of Fe and enhanced rate of post deposition relaxation in first 40 hours. The difference in growth modes of Fe film on (100) and (110) substrate arises from different reconstruction of the surface of GaAs [1] which affects the magnetic stability of film with time. We conclude that for thorough studies of dynamic magnetic properties especially in contact and reacting with the electrical properties of a semiconducting substrate it is crucial to have a flat interface and surface of film, therefore Fe\GaAs (100) is more suitable than Fe\GaAs (110). Fe\GaAs(100) can be studied without any capping layer to be especially sensitive to the interaction with the semiconducting substrate combining electrical and magnetic properties acting on picosecond timescale under UHV conditions for maximum 10 hour since it remains stable.



(a) (b)

Fig. 1. Time dependent FMR signal of Fe on (a) GaAs (100) and (b) GaAs (110) measured in-situ.

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Effect of interplay of Dzyaloshinskii-Moria and dipolar interactions on internal skyrmion structure in magnetic multilayers

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Magnetic Skyrmions are one of the fascinating and promising objects because of their small size and stability to perturbations such as electric currents and magnetic fields [1-4]. The major mechanism to stabilize small Skyrmions in ferromagnet/heavy metal bilayers is the presence of Dzyaloshinskii-Moriya interaction (DMI). In thin films, the DMI arises at the interface of ferromagnetic material and heavy metal due to the presence of spin-orbit interaction and broken inversion symmetry [4, 5].

In this work we investigate the stability and internal structure of an isolated Skyrmion in bilayer (ferromagnet/heavy metal) and trilayer (heavy metal 1/ferromagnet/heavy metal 2) nanodisks. We study the static properties of the Skyrmions and obtain the phase diagrams of the Skyrmion existence depending on the thickness of the ferromagnetic layer and the DMI strength. We demonstrate the importance of fully taking into account the dipolar interaction even for a few atomic layers thin nanodisk and that together with DMI it has the stabilizing effect and defines the Skyrmion configuration. For the trilayer structures with two heavy-metal interfaces (corresponding to two interfacial DMIs), we show that the type and configuration of the Skyrmion can be controlled by the thickness of ferromagnetic, and interplay of two interfacial DMIs can lead to formation of magnetic structures with higher winding number.

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Ba and Mn co-Doped Bismuth Ferrite ($BiFeO_3$) Nanoparticles: Tailoring the multiferroic features through phase transformation

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Multiferroic Bismuth Ferrite ($BiFeO_3$; BFO) Nanoparticles (NPs) are noteworthy suitable materials for spintronics and memory devices due to their advantageous Ferroelectromagnetic properties at room temperature. The research on BFO NPs is getting much attention due to enormous magnetic and photocatalytic behavior than their bulk counterparts.

We reported systematic study of lattice distortion and impact on the multiferroic properties due to doping of Ba and Mn in pristine BFO NPs ($Bi_xBa_{1-x}Fe_yMn_{1-y}O_3$). Crystalline doped NPs sized 30-50 nm exhibit rhombohedral (R3c) lattice symmetry with enhanced doping induced magnetization. All NPs were synthesized by modified wet chemical sol-gel route and characterized via UV-VIS absorption spectroscopy, XRD diffraction, TEM, EDX, SEM, and magnetometry. Effect of doping on multiferroic behavior was analyzed. The co-doped NPs are in 45 ± 5 nm regime and exhibit high crystallinity with no secondary phases. Tuning of optical band gap comes to possible from 2.18 to 1.91 eV. The ferromagnetic properties get enhanced by doping significantly due to distortion of spin cycloid abruptly via quantum confinement effect.

Magnetization dynamics of a single Fe_3O_4 nanoparticle chain using Scanning Transmission X-ray Microscopy Ferromagnetic Resonance and micromagnetic simulations

Thomas Feggeler[1], Benjamin W. Zingsem[1,2], Ralf Meckenstock[1], Hendrik Ohldag[3], Michael Farle[1], Heiko Wende[1] and Katharina Ollefs[1]

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For future technical developments in e. g. genetically engineered spin wave computing, as described in [1], the characterization of magnetization dynamics of magnetic nanoparticle chains, generated by biomineralization inside magnetotactic bacteria, is essential. We use Scanning Transmission Microscopy detected Ferromagnetic Resonance (STXM-FMR) and micromagnetic simulations to determine the origin of resonances in a single chain of Fe_3O_4 nanoparticles in a bacterium Magnetospirillum Magnetotacticum MS-1. The first STXM-FMR results of a double segmented chain of 19 nanoparticles (particle diameter: 50-60 nm), measured at room temperature at the Fe L_3-edge, exhibit resonances of segments of the particle chain. Simulations of a micromagnetic model of the chain geometry are in good agreement to the experimental results. The STXM-FMR setup used for the measurement offers a time resolution in the pico second range and a spatial resolution < 50 nm [2,3]. The setup is composed of a conventional Ferromagnetic Resonance (FMR) spectrometer, using micro resonators, and a Scanning Transmission X-Ray Microscope [2,3]. To detect subsequent phases of the microwave driven magnetization oscillation, the microwave signal is phase-locked to the synchrotron frequency. This allows to scan 6 phases of the magnetization oscillation with a time distance of 18 ps (9 GHz microwave frequency) and a fixed phase difference of 60 degrees [3].

Partial financial support by DFG Project: OL513/1-1 is acknowledged.
Helpful discussions with A. Ney and his team are acknowledged.

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Unidirectional anisotropy in spin-dynamics in $Fe_{50}Ge_{50}$

N. Josten[1], B.W. Zingsem[1,2], T. Feggeler[1], D. Spoddig[1], I. Radulov[3],
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Cubic $Fe_{50}Ge_{50}$ is a chiral magnet with a Curie temperature of 280 K existing in the form of two enantiomers. The inherent bulk Dzyaloshinsky-Moriya-interaction (DMI) leads to the formation of skyrmions and helical spin structures and gives rise to a non-reciprocal magnon dispersion relation. This means, that spin-waves travelling in opposite directions at the same frequency carry different momenta. We used X-band ferromagnetic resonance to study the magneto-dynamic effects of DMI on bulk polycrystalline FeGe samples close to the Curie temperature at 276 ± 1 K. Two resonance lines were observed, which unexpectedly exhibit unidirectional anisotropy, i.e. a shift of the resonance field after inversion of the external magnetic field. Additional measurements of a micron sized FeGe sample inside an R-type microresonator reveal unidirectional anisotropy in spin-wave modes as well.

Tunable saturation magnetization and low Gilbert damping of ion-irradiated FeRh thin films

Anna Semisalova[1], Rantej Bali[2], Craig Barton[3], Roman Böttger[2], Thomas Thomson[3], Kay Potzger[2], Kilian Lenz[2], Jürgen Lindner[2], Jürgen Fassbender[2]

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Structurally B2-ordered equiatomic FeRh thin films are known for unique properties such as a temperature, magnetic field, and spin polarized current driven phase transition from the antiferro- to the ferromagnetic state. The strain and structural disorder also influence the magnetic properties of FeRh, which opens a new way for controllable modification of properties at the micro- and nanoscale. Namely, structural modification by ion beam irradiation was shown to be an effective tool for tuning the phase transition temperature in FeRh as well as the saturation magnetization [1-3]. Here, we present a detailed study of magnetic properties of ion irradiated 40 nm thick FeRh films using magnetometry and broadband ferromagnetic resonance technique. The structurally ordered films were deposited epitaxially on MgO(001) substrates using magnetron sputtering. The irradiation was performed with 25 keV Ne ions with fluences of 0.1 – 4 ions/nm^2 leading to controllable reduction of the order parameter. The ion beam induced magnetization of FeRh at room temperature was shown to be as high as 1300 kA/m. Ferromagnetic resonance measurements performed at frequencies up to 40 GHz show that the Gilbert damping in structurally disordered ferromagnetic FeRh films is comparable to Py films. Such a relatively low damping in combination with the highly tuneable saturation magnetization looks attractive for further experiments with magnetization dynamics and spin wave propagation in FeRh thin films and nanostructures fabricated using ion beam irradiation.

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Internal stresses influence on functional properties of Heusler-type microwires

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Ferromagnetic shape-memory Heusler alloys have gained significant attention due to a diffusionless and reversible phase transformation exhibiting a structural transition from a cubic austenite phase with high symmetry to a martensitic phase with lower symmetry. This feature results in a number of functional properties such as magnetic shape memory effect, magnetic field-induced strain and magnetocaloric effect [1, 2]. Production of Heusler type alloys glass-coated microwires by Taylor-Ulitovsky technique allows fabrication of a long glass-coated microwires up to 10 km length with microwire diameter down to 1 micron: glass coating increases mechanical stability of the nucleus.

The influence of internal stresses on structural, magnetic properties and phase transitions of Ni-Mn-Ga and Ni-Fe-Ga glass-coated microwires was investigated. We have made an analysis a separate influence of stresses, generated during the solidification of metal and those induced by the difference between thermal expansion coefficients of metal and glass, on magnetic properties of microwires. Carrying out the heat treatment for a different time reveals the influence of the first type of stress. Removing the glass coating show the influence of the second type of stress. To analyze a complex influence of stresses we performed a heat treatment of the microwire after glass coating removal. The coercive force, saturation and remanence magnetization and Curie temperature were compared to show stresses influence. The change of easy magnetization axis direction was found for microwire with removed glass coating. A difference in surface grain size was indicated in the annealed glass-coated microwire and microwire, annealed after glass removal.

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Magnetic properties of high entropy CoCrFeMnNi alloy prepared by high energy ball milling

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A novel approach to the fabrication of a new class of alloys—also known as high-entropy alloys (HEAs) was developed by Yeh et al. [1]. The HEAs containing at least 5 components in equiatomic or nearly equiatomic amounts (ranging between 5 and 35 at. %) are attractive in terms of mechanical, thermal, electrical and magnetic properties [2]. These HEAs are stabilized by the increased mixing entropy which suppresses the formation of binary and ternary metallic phases and thus favors the formation of solid solutions of many elements.

HEAs have been fabricated by several methods, including arc melting and casting, mechanical alloying, and laser cladding. Among these, especially promising seems to be high-energy ball milling (HEBM) in planetary ball mills that can yield stable microstructures and nanocrystalline alloys of better homogeneity compared to other non-equilibrium processes [3].

We report the fabrication of CoCrFeMnNi HEA 80-120 μm particles by high-energy ball milling (HEBM) and provide their structural and magnetic characterization. Our XRD, SEM, and EDX results showed that a fcc CoCrFeMnNi solid solution with uniform distribution of the elements and refined microstructure of nanosized grains (~10 nm) could be obtained after 60 min HEBM. Magnetic studies reveal the presence of ferromagnetic (FM) and antiferromagnetic (AFM) phases below 50 K. Occurrence of exchange coupled FM and AFM phases is manifested in field-cooling (FC) induced effects [4], such as an unidirectional anisotropy (exchange bias), an increase in uniaxial anisotropy (enlarged coercivity) as well as a vertical shift of the hysteresis loop. Isothermal aging after quench down to the low temperature shows a typical features of the out-of-equilibrium dynamics of spin glass with slow relaxation processes.

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Hot carrier effects in graphene THz magneto plasmons

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Graphene is a promising material for a variety of optoelectronic applications in the THz range, e.g. detectors or modulators. One drawback of graphene is its low interaction volume, limiting the efficiency of such devices. Plasmonic structures lead to an enhanced light-matter interaction at resonance, which can increase the absorption well beyond 25%. Besides the plasmonically enhanced absorption, also a strong enhancement of nonlinear absorption in the THz range can be observed [1]. The strong nonlinearity of the absorption is caused by efficient heating of the charge carriers in the graphene, leading to a decrease in chemical potential. The drop in chemical potential leads to an ultrafast redshift of the plasmon frequency, and therewith to a strong increase in transmission at resonance. While thermal nonlinearities are usually rather slow, the hot carriers in graphene cool down to the lattice temperature within roughly 50 ps [2].

Here we study the dynamics of THz plasmons an array of micrometer sized discs of bilayer graphene on SiC. In strong magnetic fields, the plasmon hybridizes with the cyclotron motion of the charge carriers, leading to a splitting of the plasmon resonance into two branches: the upper arm merges into the cyclotron resonance while the second branch is shifted to lower frequencies. The optical response of both branches can be distinguished with circularly polarized radiation. To investigate the nonlinear plasmonic absorption, we performed pump-probe measurements with circular polarized THz pulses provided by the free-electron laser (FEL) FELBE at Helmholtz-Zentrum Dresden-Rossendorf. Magnetic fields of up to 7 T were applied with a superconducting split-coil magnet. The frequency of pump and probe pulses was tuned slightly below resonance, the change in probe transmission was measured as a function of pump-probe time delay at various magnetic fields. Without magnetic field, the observed change in probe transmission is about 2% at a pump fluence of 21 nJ/cm^2. Increasing the magnetic field successively to 7 T first leads to an increase of the signal before it drops off to zero at around 5 T. Changing the sign of the magnetic field leads to a strong change in the observed signals: as the FEL polarization is kept constant, changing the sign of the magnetic field corresponds to measurements on the second branch of the magneto plasmons. In this case we observed a change in sign, i.e. a pump-induced decrease in transmission. Results of a hot carrier model are in good qualitative agreement with experiments.

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Synthesis of epitaxial Cr_2AlC MAX phase films by pulsed laser deposition

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MAX phases ($M_{n+1}AX_n$) are ternary or quaternary compounds of layered hexagonal structures, where M is an early transition metal, A is an A group element and X is either C or N. They are objects of extended studies due to their unique and intriguing properties as they show combined characteristics of metals (high thermal and electrical conductivity and resistance to thermal shocks) and ceramics (elastically rigid, lightweight and resistance to oxidation) [1]. Due to the layered structure, MAX phases exhibit highly anisotropic electrical [2] and thermal transport properties which, for example, makes them prime candidates for heat sink layers in heat assisted magnetic recording media [3]. Within the last years, much attention is put on magnetic MAX phases with Cr and/or Mn as two possible M elements. The magnetic properties of such $(M1_xM2_{1-x})_2AX$ phases are driven by competing ferromagnetic and antiferromagnetic correlations leading to complicated phase diagrams [4,5]. One parent compound of such MAX phases is Cr_2AlC.

In this work, we show the first successful synthesis of epitaxial Cr_2AlC films on MgO (111) substrates by pulsed laser deposition (PLD) with film thicknesses of 10-50 nm. In Figure 1(a) we present the X-ray diffraction of the 10 and 50 nm films, as well as the corresponding pole figure for the 50 nm film. The epitaxial relation is Cr_2AlC (0001) || MgO (111) in the growth direction and Cr_2AlC $[11\bar{2}0]$ || MgO $[10\bar{1}]$ in the film plane as determined by the pole figure on the $[10\bar{1}3]$ MAX phase peak. Figure 1(b) shows a scanning electron microscopy (SEM) image of the surface of the 50 nm film. We observe a homogeneous film growth besides Al droplets being a typical side product in PLD. Furthermore, we investigated the electrical conductivity as function of temperature and observe a typical metallic behaviour with a residual resistance ratio of 1.63.

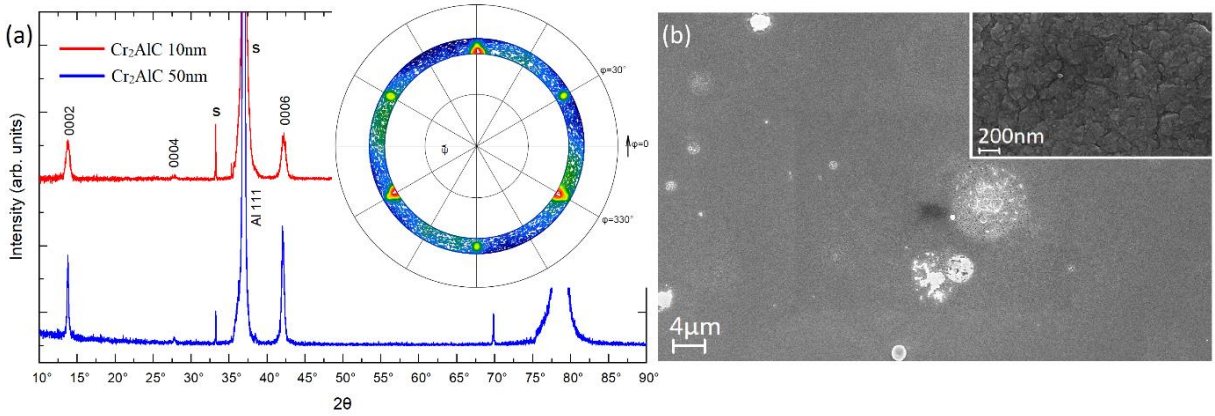

Figure 1: (a) X-ray diffractograms of 10 and 50 nm Cr_2AlC films on MgO (111) and the pole figure of the Cr_2AlC $[10\bar{1}3]$ 50 nm film deposited at 600°C. (b) presents a SEM image of a 50 nm film. The inset shows a magnification showing the columnar growth.

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Paramagnetic molecules on Fe_3O_4 – Au nanoparticles as a spin-current detector

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Pure spin current-based devices are considered for future low-dissipation electronics. A common method for spin current detection is the inverse spin Hall effect (ISHE) based on a voltage measurement in a metallic layer with strong spin-orbit coupling [1]. Recently, we presented an alternative spin current detection method using an interfacial molecular paramagnet as a spin current detector (IMPSD) [2, 3]. Here we present an extended version of the IMPSD with enhanced sensitivity.

We have chosen octahedral Fe_3O_4 nanoparticles (NPs) with a diameter of 15 nm grown on Au NP seeds in presence of oleic acid (OA) as a surfactant [4]. Due to the synthesis at 310 °C OA has two paramagnetic centers, one directly at OA-NP interface and the other one at the double bond in the alkyl chain [4]. We use the ferromagnetic resonance (FMR) of the Fe_3O_4 NPs for generating a spin current at the OA-NP interface. Due to the magnetic shape anisotropy of the sample, the angular-dependent FMR signal of the NPs can be superimposed with the EPR signals of OA. We detect the impact of the spin current on the EPR centers. This is resulting in an additional contribution to the power dependence of the two EPR modes. As expected, the first EPR signal S1 with a linewidth of 24 mT is linearly increasing with the square root of the microwave power, already shown in [1]. From the difference in slope with or without superimposing FMR and EPR one can derive the spin current.

Here we show that the second EPR signal S2 at the OA double bond with an extremely sharp linewidth of < 0.1 mT acts as an enhanced spin current detector. The signal S2 decreases exponentially with increasing microwave power. We explain this by pumping of S2 by S1 due to their different lifetimes, i.e. the population inversion of S2.

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