Spin Transport in Complex Magnetic Structures

710. WE-Heraeus-Seminar

08 – 10 January 2020
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 710. WE-Heraeus-Seminar:

In this seminar we will discuss spin-dependent transport in complex magnetic materials. This transport physics is at the heart of many established and currently investigated spintronic applications. Spin transport is a major driver behind the tremendous increase of information storage capabilities taking place over the last decades. As such, it has shaped the transformation into a knowledge society. To continue this success story and contribute to global trends like digitalization and artificial intelligence, new materials, new methods and new ideas are mandatory. When spin angular momentum is transported in space and time through complex magnetic materials, structures or textures, such currents can interact with the transport medium, and eventually change its dynamical or static state. In particular, the aspect of active control due to this interaction generates a multitude of potential applications for spin transport in complex magnetic structures. The central aim of this seminar is to bring together researchers working at the forefront of material research, and others who develop and apply novel methods to image magnetic properties in such materials, with the scientists who directly investigate spin transport physics on a fundamental level and for applications. For this purpose, renown scientists will summit together with young talents.

Scientific Organizers:

Dr. Matthias Althammer	Walther-Meißner-Institut, Garching, Germany E-mail: matthias.althammer@wmi.badw.de
Dr. Henning Ulrichs	Universität Göttingen, Germany E-mail: hulrich@gwdg.de

Program

Program

Tuesday, 07 January 2020

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and get-together*	

Wednesday, 08 January 2020

08:00	*BREAKFAST*	
08:45 – 09:00	Scientific organizers	**Welcome & opening remarks**
09:00 – 09 :45	Andras Kovacs	**Quantitative measurements of magnetic fields in a transmission electron microscope**
09:45 – 10:30	Claire Donnelly	**Mapping three dimensional magnetic systems**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Christian Tusche	**Electron correlations and Fermi surface topology of itinerant ferromagnets mapped by momentum microscopy**
11:45 – 12:15	Sergey Zayko	**Ultrafast magneto-optical microscopy using high-harmonic radiation**
12:15 – 12:30	**Conference Photo** (in the front of the lecture hall)	
12:30	*LUNCH*	

Wednesday, 08 January 2020

14:00 – 14:45	Aisha Aqeel	**New skyrmion resonance modes in a chiral magnetic insulator**
14:45 – 15:30	Markus Meinert	**Role of thermal activation in the spin-orbit torque switching of antiferromagnets**
15:30 – 16:00	Artem Pulkin	**Electronic and spin transport properties of two-dimensional transition metal dichalcogenides**
16:00 – 16:45	Evangelos Papaioannou	**Defect engineering of spintronic terahertz emitters**
16:45 – 17:15	*COFFEE BREAK*	
17:15-18:30	**1-Slide Poster Presentations**	
18:45	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	
20:00	**Poster Session**	

Program

Thursday, 09 January 2020

08:00	*BREAKFAST*	
09:00 – 09:30	Olena Gomonay	**Magnon transport in antiferromagnets: the role of domains**
09:30 – 10:15	Patrick Maletinski	**Probing nanoscale magnetism using single spin**
10:15 – 10:45	*COFFEE BREAK*	
10:45 – 11:30	Sangeeta Sharma	**Ultrafast spin dynamics: TDDFT's killer app.**
11:30 – 12:15	Ulrike Ritzmann	**High-frequency magnon excitation due to femtosecond spin-transfer torques**
12:30	*LUNCH*	
14:00 – 14:45	Boris Divinskiy	**Controlled nonlinear magnetic damping in spin-Hall nano-devices**
14:45 – 15:15	Katrin Schultheiß	**Stimulated 3-magnon scattering in magnetic vortex structures**
15:15 – 16:00	Tobias Kampfrath	**Terahertz spin transport in magnetic nanostructures**
16:00 – 16:45	Alexander Mook	**Origin of the magnetic spin Hall effect: spin current vorticity in the Fermi sea**
16:45 – 17:15	*COFFEE BREAK*	
17:15 – 18:30	**Poster Session**	
19:00	*DINNER*	
20:00 – 20:45	Kevin Garello	**Spin-Orbit Torque MRAM for ultrafast embedded memories: from fundamentals to large scale technology integration and future challenges**

Program

Friday, 10 January 2020

08:00	*BREAKFAST*	
09:00 – 09 :45	Can Onur Avci	**Electrical manipulation and detection of magnetic insulators with perpendicular anisotropy**
09 :45 – 10:30	Hans Huebl	**Controlling magnon transport in ferrimagnetic insulators**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Felix Büttner	**Electrical and optical manipulation of magnetic skyrmions and chiral domain walls**
11:45 – 12:15	Rouven Dreyer	**Phase-resolved imaging of non-linear spin-wave generation at low magnetic bias field**
12:15 – 12:30	Scientific organizers	**Closing Remarks & Awards**
12:45	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Saturday morning

Posters

Posters

Valentin Ahrens	**FIB written artificial Skyrmion bubble lattices in Pt/Co/HM-Multilayers**
Kyongmo An	**Long range coupling of magnetic bi-layers by coherent phonons**
Maria Azhar	**Surface states and all electrical detection of skyrmions in a chiral magnetic insulator**
Christian Back	**REXS-FMR: a novel method for the determination of dynamic modes in complex magnetic materials**
Sven Becker	**Interfacial Dzyaloshinskii-Moriya interaction and chiral magnetic textures in a ferrimagnetic insulator**
Yannic Behovits	**Ultrafast spin dynamics in antiferromagnetic Mn_2Au**
Thomas Feggeler	**Biomagnonic logic device concepts: A new approach to spintronics?**
Luis Flacke	**Chiral magnetic texture and spin dynamics in magnetic superlattices**
Pascal Frey	**Reflection-less width-modulated magnonic crystals**
Dongwook Go	**Current-induced orbital angular momentum and orbital torque for spin-orbitronics**
Janine Gückelhorn	**Magnon transport in three-terminal magnetically ordered insulator/platinum nanostructures**
Oliver Gueckstock	**Impact of the interface on ultrafast spin-to-charge conversion in metallic bilayers**
Christopher Heins	**Growth and characterization of YIG nano-films grown by metal-organic aerosol deposition**

Posters

Fabian Kammerbauer	**Topological spin structures in a ferromagnetic monolayer**
Lukas Körber	**Theory and simulation on nonlinear spin-wave dynamics in magnetic vortices**
Adamantia Kosma	**Spin-orbit torque effect in the surface of Bi_2Te_3 doped with magnetic transition-metal defects**
Stephanie Lake	**Spin-hall nano-oscillators, optimized shape and fabrication strategies**
Olga Lozhkina	**Periodical magnetic wire width modulation for reliable domain wall propagation in sensor applications**
Sergiy Mankovskyy	**Chirality-induced linear response properties in hexagonal Mn_3Ge**
Franziska Martin	**Current induced chiral domain wall motion by spin-orbit torques in CuIr/CoFeB/MgO thin films**
Simon Mendisch	**Perpendicular nanomagnetic logic based on low anisotropy Co\Ni multilayer**
Daniel Metternich	**Non-equilibrium spin dynamics and statics enforced by spin currents in nano-YIG films**
Dennis Meyer	**THz spin-wave generation in optically-driven acoustic resonators**
Mohammad M. Qaid	**Spin-charge conversion and spin relaxation mechanism in highly-doped π-conjugated polymer PBTTT**
Christina Möller	**A novel high flux XUV light source for the study of ultrafast element-specific magnetization dynamics**
Marcel Möller	**Ultrafast Lorentz microscopy: A tool to study laser- and current-driven magnetization dynamics**

Posters

Timo Noack	**Enhancement of the spin pumping effect by magnon confluence process**
Matthias Opel	**Spin hall magnetoresistance in antiferromagnetic insulators**
Maximilian Paleschke	**Static and time-resolved photoemission electron microscopy of magnetization dynamics triggered by back-side illumination**
Bastian Pfau	**Small-angle x-ray scattering from nanoscale transient magnetic gratings**
Santa Pile	**Direct imaging of the localized spin dynamics in confined micro structures using time-resolved STXM**
Henrike Probst	**Study of ultrafast magnetization dynamics in perovskite oxide thin films by use of extreme ultraviolet light**
Alexander Schäffer	**Twisting and tweezing the spin wave: on vortices, skyrmions, helical waves, and the magnonic spiral phase plate**
Richard Schlitz	**Imaging and writing magnetic domains in the non-collinear antiferromagnet Mn_3Sn**
Christin Schmitt	**Current induced switching of epitaxial NiO(111)/Pt and CoO(001)/Pt bilayers**
Severin Selzer	**Domain wall dynamics of ferrimagnets in thermal magnon currents**
Tanja Strusch	**Paramagnetic molecuels on magnetite as a spin-current detector**
Sahitya Vegesna	**towards room temperature ferromagnetism in magnetic ZnO with stable bound magnetic polarons**

Clemens von Korff Schmising	**Optical intersite spin transfer probed by helicity dependent transient absorption spectroscopy**
Jakob Walowski	**Efficiency of ultrafast optically-induced spin transfer in Heusler compounds**
Mathias Weiler	**Exchange-enhanced ultrastrong magnon-magnon coupling in a compensated ferrimagnet**
Rui Wu	**Spin-orbitronics based on a vdW antiferromagnetic semiconductor**

Abstracts of Talks

(in chronological order)

Quantitative measurements of magnetic fields in a transmission electron microscope

A. Kovács[1] and R.E. Dunin-Borkowski[1]

[1]*Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich, 52425 Jülich, Germany*

Two and three dimensional (3D) magnetic structures represent sizeable challenges for characterisation and measurement of magnetic states and properties. In a transmission electron microscope (TEM), the electron wave that passing through the sample, is deflected and acquires a characteristic phase shift that can be used to quantitatively measure the in-plane magnetic field distributions in nanostructures and nanometer sized complex spin textures as a function of applied magnetic field, electrical bias and temperature. Here we discuss the different techniques that TEM can offer to measure magnetic fields, in particular the recent advances in Lorentz microscopy and off-axis electron holography [1]. Various examples are discussed including magnetic nanostructures, magnetic spin textures (e.g. skyrmions [2]) and domain walls in soft and hard magnetic materials. The electron phase measurements are also combined with a model-based reconstruction algorithm to measure the projected in-plane magnetisation quantitatively and micromagnetic simulations. We assess the prospects of vector field tomography with sub-10 nm resolution obtained by recording tilt series of electron phase images.

References

[1] A. Kovács, R.E. Dunin-Borkowski, *Magnetic imaging of nanostructures using off-axis electron holography,* Handbook of Magnetic Materials, Vol. **27**. 59 (2018)

[2] F. Zheng et al., *Experimental observation of chiral magnetic bobbers in B20-type FeGe,* Nature Nanotechnology **13**, 451 (2018)

Mapping Three Dimensional Magnetic Systems

C. Donnelly[1]

[1]University of Cambridge, Cavendish Laboratory, JJ Thomson Ave, Cambridge, UK

Three dimensional magnetic systems promise significant opportunities for applications, for example providing higher density devices and new functionality associated with complex topology and greater degrees of freedom [1]. For the experimental realisation of these new properties, appropriate fabrication, and characterisation techniques are required.

We have developed X-ray magnetic nanotomography [2], combining a new iterative reconstruction algorithm [3] with a dual rotation axis experimental setup, therefore providing access to the three-dimensional magnetic configuration at the nanoscale. In a first demonstration, we have determined the complex three-dimensional magnetic structure within the bulk of a micrometre-sized soft magnetic pillar and observed a complex magnetic configuration that consists of vortices and antivortices, as well as Bloch point singularities [2].

Moving to alternative experimental geometries opens up new possibilities for the experimental investigation of three-dimensional nanomagnetic systems. In particular, with our recent development of X-ray magnetic laminography, ideally suited for the study of flat samples, it is now possible to determine the magnetisation dynamics of a three-dimensional magnetic system [4]. The capabilities of X-ray magnetic tomography and laminography open the door to the elucidation of the complex three-dimensional magnetic structures, and their dynamic behaviour.

[1] Amalio Fernández-Pacheco, Robert Streubel, Olivier Fruchart, Riccardo Hertel, Peter Fischer and Russell P. Cowburn, Nature Comm. 8, 15756 (2017).

[2] C. Donnelly, M. Guizar-Sicairos, V. Scagnoli, S. Gliga, M. Holler, J. Raabe and L. J. Heyderman, Nature 547, 328 (2017).

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Electron correlations and Fermi surface topology of itinerant ferromagnets mapped by momentum microscopy

C. Tusche[1,2]

[1]Peter Grünberg Institut (PGI-6), Forschungszentrum Jülich, Jülich, Germany
[2]Fakultät für Physik, Universität Duisburg-Essen, Duisburg, Germany

A fundamental concept in solid state physics describes the degrees of freedom of electrons in a solid by the relation of the energy E vs. the crystal momentum k in a band structure of independent quasi particles. In a real electron system, exchange- and correlation interaction are collective phenomena that lead, for instance, to effects like ferromagnetism. Consequently, for the 3d ferromagnets Fe, Ni, and Co, a description of the band structure in the widely used local density approximation (LDA) is of limited use, as seen by the fact that predicted well defined electronic bands are not observed experimentally. Only recently, experimental access to the spin resolved band structure at every point in the Brillouin zone became feasible by spin-resolved momentum microscopy [1]. This novel concept combines high resolution imaging of photoelectrons in two-dimensional (k_x, k_y) maps with a highly efficient imaging spin filter [2].

Our comprehensive measurements of the spectral-function by spin-resolved momentum microscopy give evidence that in itinerant ferromagnets like cobalt electron correlations are of nonlocal origin. This manifests in a complex self-energy that disperses as function of spin, energy, and momentum. Together with one-step photoemission calculations, we quantify the dispersion of the self-energy over the whole Brillouin zone [3]. The observation of nonlocal electron correlations in cobalt substantially affects our understanding of electron interactions, and makes itinerant ferromagnets a paradigmatic test case for the interplay between band structure, magnetism, and correlations.

Moreover, the interplay of strong spin-orbit interaction and ferromagentism can give rise to novel complex spin textures in the Fermi surface. In addition to unveiling the comprehensive spin-orbital textures of such complex magnets, we will address simultaneous changes in the spin-resolved Fermi surface topology with broken fundamental symmetries.

References

[1] C. Tusche, A. Krasyuk, J. Kirschner, Ultramicroscopy 159, p. 520 (2015)
[2] C. Tusche, et al., Appl. Phys. Lett. 99, 9, 032505 (2011)
[3] C. Tusche et al., Nat. Commun. 9, 3727 (2018)

Ultrafast magneto-optical microscopy using high-harmonic radiation

S. Zayko[1], O. Kfir[1], M. Heigl[2], J. Hagen[1], M. Sivis[1], M. Albrecht[2], and C. Ropers[1]

[1]*IV Physical Institute, University of Göttingen, Germany*

[2]*Experimentalphysik IV Institut für Physik Universität Augsburg, Germany*

The dynamics of magnetic systems span a vast range of spatial and temporal scales. In a recent push towards magnetic technology development, substantial efforts are made to allow for the demonstration of THz dynamics driving frequencies of nano-scale magnetic features, such as domain walls and Skyrmions [1-3], for new generation storage and logic devices. For such endeavors, the combination of both space and time at the ultimate scales is essential [4]. To date, there are tools providing insights to either spatial magnetic structure [5], or temporal magnetic dynamics [6], with extreme precision, separately.

In this work, we demonstrate ultrafast magnetic microscopy enabling high spatial and temporal resolution using a lab-based source. Utilizing magnetic circular dichroism imaging based on high-harmonic radiation [7], we record movies of magnetic domains following an abrupt optical excitation by a short laser pulse. These movies provide for a 40 fs temporal resolution combined with spatial resolution of 40 nm. To establish the capabilities of our system, we demonstrate imaging of a magnetic domain patterns with spatial resolution down to 16 nm, well below the illumination wavelength of 21 nm. Additionally, we demonstrate laser induced nucleation of various spin textures ranging from nanoscale domains to magnetic bubbles and Skyrmions. Due to the available spectral range from high-harmonic generation process, this scheme covers element specific studies of important magnetic materials including iron cobalt and nickel as well as ferrimagnetic compounds even at their compensation points. Given the accessibility of compact lab-based high-harmonic sources and the unprecedented resolution they may offer, we believe that this versatile ultrafast magneto-optical microscope will become an indispensable tool for comprehensive research of fundamental aspects of magnetism, as well as for application-oriented investigations.

[1] L. Caretta et al., Nature Nanotechnology, **13**, pages1154–1160 (2018)

[2] K-J. Kim et al., Nature Materials, **16**, pages1187–1192 (2017)

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New skyrmion resonance modes in a chiral magnetic insulator

A. Aqeel[1], J. Sahliger[1], T. Taniguchi[1], D.Mettus[1], A. Bauer[1], M. Garst[2], C. Pfleiderer[1], C.H. Back[1]

[1]Department of Physics, Technical University of Munich, Garching, Germany

[2]Institute for Theoretical Solid State Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany

Email: aisha.aqeel@tum.de

Recently, a new independent low-temperature skyrmion (LTS) phase has been discovered [1] in addition to the previously observed high temperature skyrmion pocket [2] in a chiral magnetic insulator Cu_2OSeO_3. Unlike high temperature skyrmion pocket, the LTS phase has a different stabilization mechanism favored by the cubic anisotropy contribution [1,3]. The key question here is how a different stabilization mechanism would influence the magnetization dynamic and modify the magnetic resonant response of skyrmions. Using a spin-wave spectroscopy technique, we systematically track the magnetic resonance response in different magnetic phases of Cu_2OSeO_3, focusing on the LTS phase at 5K. We identify distinct resonances associated with the newly discovered tilted conical and LTS phases of Cu_2OSeO_3. We observed a strong dependence of these modes on static magnetic field history. We identified an increase in the weights of skyrmion resonance modes by cycling magnetic field within this phase. The magnetic phase boundaries and effect of field cycling on the population of different phases agrees well with our magnetometery measurements. To understand the observed resonance spectra, we used a phenomenological model based on previous work [4] with an addition consideration of different cubic anisotropy contributions. Our theoretical model confirms that the cubic anisotropy contribution is the key ingredient for the observed resonance spectra. We believe that these results will be instrumental for existing possibilities for future skyrmion based microwave devices.

References

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Role of thermal activation in the spin-orbit torque switching of antiferromagnets

Markus Meinert[1]

[1]Department of Electrical Engineering and Information Technology, Technical University Darmstadt, Darmstadt, Germany

Electrical manipulation of antiferromagnets offers the prospect of creating novel, antiferromagnetic spintronic devices [1]. Such devices aim to make use of the insensitivity to external magnetic fields and the ultrafast dynamics at the picosecond timescale intrinsic to antiferromagnets. The possibility to electrically switch antiferromagnets was first predicted for Mn2Au [2] and then experimentally observed in tetragonal CuMnAs [3]. Later, the switching was also verified in Mn2Au [4]. More recently, electrical switching of NiO [5,6], Fe2O3 [8], and MnN [9] with the spin Hall effect of Pt was demonstrated. This makes a much larger class of materials available to antiferromagnetic spintronics and allows for separate tuning of spin-orbit torque efficiency and magnetic stability.

In this talk, I will review the role of thermal activation on the switching and the relaxation of electrically set Neel configurations. Due to the weak spin-orbit torque effective fields, materials that allow for easy switching of the Neel order will typically show fast relaxation of the magnetic order to a random configuration. The Joule heating of the electrical current can assist the switching by making grains of the antiferromagnet switchable, which are stable at the device operating temperature, effectively freezing the magnetic state after turning off the current. I will show typical characteristics of the thermal activation-related behaviour in systems driven by the Neel-order spin-orbit torque as well as in systems driven by the spin Hall effect.

Finally, I discuss an artifact seen in electrical switching experiments which arises from current-induced local heating in the Hall cross devices. X-ray microdiffraction and scanning electron microscopy in combination with finite-element simulations reveal the origin of the artifact and allow for its quantitative understanding.

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[8] M. Dunz et al., arXiv:1907.02386

Electronic and spin transport properties of two-dimensional transition metal dichalcogenides

A.Pulkin[1] **and O.V.Yazyev**[2]

[1] *QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands*

[2] *École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland*

Two-dimensional transition metals dichalcogenides (2D TMDs) attracted much attention due to their unique electronic properties and a large potential for device fabrication. In the talk I will present several examples of how charge carrier spins and the spin-orbit coupling can be employed to modulate electronic transport properties in the family of materials. First, I will demonstrate the spin discrimination in charge carrier ballistic transport without time-reversal symmetry breaking in semiconducting 2D TMDs. Second, I will discuss realistic edges of the quantum spin Hall (QSH) phase in 2D TMDs hosting topologically-protected spin-polarized modes. I will also demonstrate how the bulk band gap in the QSH phase can be increased by tensile strain. These findings provide an avenue towards fabrication of 2D all-electric logic devices operated by charge carrier spins.

References

[1] A. Pulkin and O. V. Yazyev, *Phys. Rev. B* **93**, 041419 (2016)

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Defect engineering of spintronic terahertz emitters

Evangelos Papaioannou

Institute of Physics, Martin-Luther University Halle-Wittenberg, Germany

Spintronic ferromagnetic (FM) / non-magnetic (NM) heterostructures are novel sources for the generation of THz radiation based on spin-to-charge conversion in the layers. The key technological and scientific challenge of THz spintronic emitters is to increase their intensity and frequency bandwidth. In this presentation, we review the field of THz spintronics and based on our recent results, we provided a roadmap of THz emission that is essential for future applications of metallic spintronic THz emitters (Fig. 1a) [1].

In particular, we demonstrate the ability to control the emitted THz spectra by modifying (i) the defect density that results in changing the elastic electron-defect scattering lifetime in the FM and NM layers and (ii) the FM/NM interface transmission for spin-polarized, non-equilibrium electrons. A decreased defect density increases the electron-defect scattering lifetime and this results in a significant enhancement of the THz-signal amplitude and shifts the spectrum towards lower THz frequencies (Fig. 1b). Defect-free epitaxial emitters yield the highest emitted-field amplitude. The spectral width can be further controlled by introducing defects in the sample, which decrease the elastic scattering time at the cost of lower peak-field amplitudes. The interface transmission is correlated to the local FM/NM interface morphology and it influences the spectral amplitude but conserves the frequency composition of the spectrum.

In conclusion, our experimental and theoretical study forecasts the THz-pulse shapes and spectra and thereby paves the way for the technological development of THz emitters.

(a) (b)

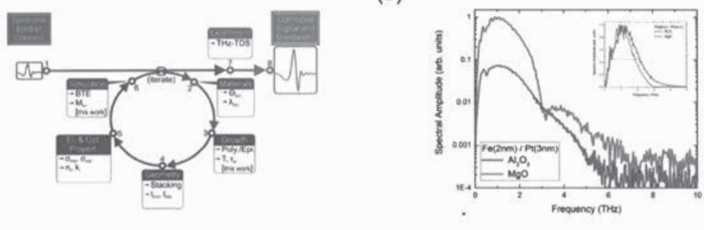

Fig. 1a: Roadmap to efficient spintronic THz-emitters for high signal strength and broad bandwidth.

Fig. 1b: Experimental THz-E-field amplitudes for samples with different degree of structural defects.

References

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Magnon transport in antiferromagnets: the role of domains

O. Gomonay

JGU, Mainz, Germany

Spin transport mediated by magnon propagation is a promising tool for information transmission in spintronics devices. Among different magnetic media antiferromagnetic insulators stand out, as they potentially provide high magnon velocity, long propagation length, and at least two types of spin states for propagating magnons. In this paper we discuss peculiarities of the magnonic spin transport in an archetypical antiferromagnet Cr_2O_3 (hematite) which shows variety of the magnetic phases accessible through variation of the external magnetic field and temperature [1]. Addressing typical experimental set-up we assume local spin injection from a heavy metal electrode and calculate thus induced spin-polarized magnon fluxes for different values of field and temperature. In a single-domain state of uniaxial phase spin current decays exponentially in space, as the spin propagation length is limited mainly by spin diffusion. In easy-plane phase the spin current can be suppressed by dephasing of the spin-carrying superposition of magnons. In a multidomain state additional attenuation of spin current steams from the magnon scattering at the domain walls. We calculate corresponding reflection/transmission coefficients for different magnon modes assuming magnetoelastic mechanism of the domain wall pinning. We find that the magnon scattering is significant up to a critical value of the wavevector, k_{crit}, which is proportional to the pinning field. The low frequency magnons with $k<k_{crit}$ are effectively scattered by the domain walls and their propagation length is dominated by the domain size L. The high frequency magnons with $k>k_{crit}$ diffuse with a characteristic length λ typical for a single-domain sample. If both types of magnons ($k<k_{crit}$ and $k>k_{crit}$) contribute into spin current, the space dependence of spin-related signal shows two characteristic decay length, L and λ, which can be used to probe the domain structure of the sample. On the other hand, selective excitations of high frequency modes and coarsening of the domain structure can increase spin propagation length important for the functionalization of antiferromagnetic spintronic devices.

References

[1] A. Ross, R. Lebrun, O. Gomonay et al, arXiv:1907.02751 (2019)

Probing nanoscale magnetism using single spin magnetometry

P. Maletinsky

[1]*Department of Physics, Basel University, Klingelbergstrasse 82, 4056 Basel, Switzerland*

Electronic spins yield excellent quantum sensors which enable quantitative, nanoscale imaging even down to the level of single spins [1]. I will describe the basic working principles and technological advances [5] of these nanoscale quantum sensors and highlight some of their recent scientific applications to open questions in condensed matter physics.

Specifically, I will discuss how we employ single electronic spins in diamond for nanoscale probing of antiferromagnetic systems [7] and high-resolution imaging of atomically thin "van der Waals" magnets[11]. For both, the combination of sensitivity, spatial resolution and quantitative imaging enables unprecedented insights such as quantitative, in-situ determination of magnetic moment densities or the imaging of nanoscale domains.

I will conclude with an outlook of future developments of single spin magnetometers for extreme conditions, such as high magnetic fields, millikelvin temperatures or for high-frequency sensors to probe the dynamics of nanomagnetic systems.

References

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Ultrafast spin dynamics: TDDFT's killer app.

Sangeeta Sharma[1] and J. K. Dewhurst[2]

[1]*Max Born institute, Maxborn strasse 2A, 12489 Berlin,Germany*
[2] Max Planck institute, weinberg 2, 06120 Halle, Germany

I will talk about all-optical switching of long-range magnetic order. The type of coupling between the constituent atoms of a magnetic solid, usually ferromagnetic (FM) or anti-ferromagnetic (AFM), is a fundamental property of any magnetic material. This coupling is governed by the exchange interaction, for which the time scale of a typical magnetic material is of the order of a few 100s of femtoseconds. In our work, using time-dependent density functional theory (TDDFT), we demonstrate that a rich control over magnetization at sub-exchange time scales (of the order of few tens of femtoseconds) is possible[1,2,3,4]. This even includes changing the magnetic order from AFM to FM[5]. By investigating a wide range of multi-sublattice magnetic materials we are able to formulate three simple rules that predict the qualitative dynamics of magnetization for ferromagnetic, anti-ferromagnetic, and ferri-magnetic materials on sub-exchange time scales.

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High-frequency magnon excitation due to femtosecond spin-transfer torques

U. Ritzmann[1], P. Balaz[2,3], P. Maldonado[4], K. Carva[2] and P. M. Oppeneer[4]

[1] *Dahlem Center of Complex Quantum Systems and Department of Physics, Freie Universität Berlin, Berlin, Germany*
[2] *Department of Condensed Matter Physics, Charles University, Prague, Czech Republic*
[3] *IT4 Innovations Center, VSB Technical University of Ostrava, Ostrava-Poruba, Czech Republic*
[4] *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden*

Femtosecond laser pulses can induce ultrafast demagnetization as well as generate bursts of hot electron spin currents. In trilayer spin valves consisting of two metallic ferromagnetic layers separated by a nonmagnetic one, the laser-induced spin currents propagates from the first ferromagnetic layer through the spacer reaching the second magnetic layer. When the magnetizations of the two magnetic layers are noncollinear, the spin current exerts a torque on magnetic moments in the second ferromagnet. Since this torque is acting only within the sub-ps timescale, it excites coherent high-frequency magnons as recently demonstrated in experiments [1].

We have explored the effect of ultrafast demagnetization in noncollinear magnetic configurations and spin transfer torque using the generalized spin-dependent superdiffusive transport model [2]. We simulated the response of the magnetic system to the resulting ultrashort spin-transfer torque pulse by means of atomistic spin dynamics simulations. Our results confirm that these ultrashort hot-electron spin currents excite magnons with frequencies larger than 1THz [3], a frequency range out of reach for current induced spin-transfer torques. We study the formation of thickness-dependent standing spin waves during the first picoseconds after laser excitation. In addition, we analyze the influence of the penetration depth of the spin-transfer torque on the excited magnons. Our simulations clearly show a suppression effect of magnons with short wavelengths already for penetration depths in the range of 1nm confirming experimental findings reporting penetration depths below 2nm. These results offer a new pathway to excite high-frequency magnons in the THz regime, which allows for new design concepts for ultrafast spintronics and high-frequency magnonics applications. The developed theory can be used to tailor the trilayer composition so that the desired magnonic contribution is enhanced.

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Controlled nonlinear magnetic damping in spin-Hall nano-devices

B. Divinskiy[1], S. Urazhdin[2], S. O. Demokritov[1], and V. E. Demidov[1]

[1]*University of Münster, Münster, Germany*
[2] *Emory University, Atlanta, USA*

Large-amplitude magnetization dynamics is substantially more complex compared to the low-amplitude linear regime, due to the inevitable emergence of nonlinearities. One of the fundamental nonlinear phenomena is the nonlinear damping enhancement, which imposes strict limitations on the operation and efficiency of magnetic nanodevices. In particular, nonlinear damping prevents excitation of coherent magnetization auto-oscillations driven by the injection of spin current into spatially extended magnetic regions. Here, we propose and experimentally demonstrate that nonlinear damping can be controlled by the ellipticity of magnetization precession. By balancing different contributions to anisotropy, we minimize the ellipticity and achieve coherent magnetization oscillations driven by spatially extended spin current injection into a microscopic magnetic disk. Our results provide a novel route for the implementation of efficient active spintronic and magnonic devices driven by spin current.

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Stimulated 3-magnon scattering in magnetic vortex structures

K. Schultheiss,[1] **L. Körber,**[1,2] **R. Verba,**[3] **T. Hula,**[1] **A. Kákay,**[1] **J. Fassbender,**[1,3] **and H. Schultheiss**[1,3]

[1]Institut für Ionenstrahlphysik und Materialforschung, Helmholtz-Zentrum Dresden – Rossendorf, D-01328 Dresden, Germany
[2]TU Dresden, D-01062 Dresden, Germany
[3]Institute of Magnetism, National Academy of Sciences of Ukraine, Kyiv 03142, Ukraine

Magnetic vortices in micrometer-sized disks offer a very rich eigenspectrum and provide an ideal playground to investigate nonlinear magnetization dynamics. In the past, we demonstrated that due to highly efficient 3-magnon scattering, this system is predestined to excite whispering gallery magnons [1]. These eigenmodes exhibit very large azimuthal mode numbers and show a pronounced localization at the boundary of the disk, which makes them ideal candidates to study the coupling of magnetic vortices to optical cavities hosting optical whispering gallery modes. Furthermore, the charactersitc threshold behaviour of the observed 3-magnon scattering may be promising to form complex nonlinear networks.
Here, we present a new way to control 3-magnon scattering in a coupled system of a magnetic vortex and an adjacent waveguide. We will demonstrate in micromagnetic simulations and experiments, that it is possible to induce the 3-magnon-scattering process even below threshold and open silent scattering channels, that are not readily populated above threshold.

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Terahertz spin transport in magnetic nanostructures

Tobias Kampfrath[1,2]

[1]Department of Physics, Freie Unversität Berlin, Germany
[2]Fritz Haber Institute of the Max Planck Society, Berlin, Germany

Transport of spins is often driven by heat gradients and electric fields. To probe the initial elementary steps which lead to the formation of spin currents, we need to launch and measure transport on femtosecond time scales. This goal is achieved by employing both ultrashort optical and terahertz electromagnetic pulses. We illustrate our experimental approach by several examples including the spin Seebeck effect (see figure) and anisotropic magnetoresistance.

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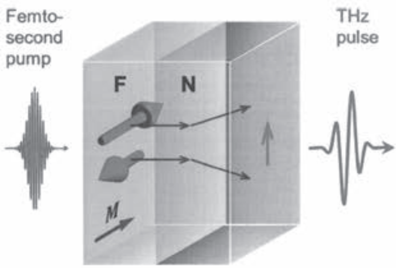
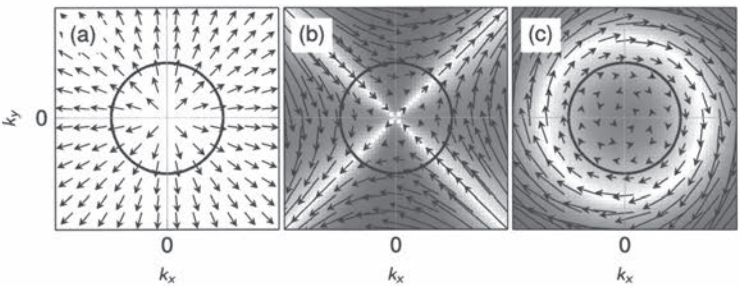


Origin of the Magnetic Spin Hall Effect: Spin Current Vorticity in the Fermi Sea

<u>A. Mook</u>[1], R. R. Neumann[2], A. Johansson[2], J. Henk[2] and I. Mertig[2,3]

[1]*Department of Physics, University of Basel, Basel, Switzerland*
[2]*Institute of Physics, Martin Luther University Halle-Wittenberg, Halle, Germany*
[3]*Max Planck Institute for Microstructure Physics, Halle, Germany*

The spin Hall effect (SHE) is a reliable working horse in the field of spintronics for the generation and detection of spin currents. Being a time-reversal even effect, the SHE is featured in normal metals like platinum. However, magnetic materials not only exhibit the SHE but also its "(time-reversal) odd cousin" [1], which was dubbed magnetic SHE (MSHE) [2]. In contrast to spin accumulations brought about by the SHE, those of the MSHE reverse direction under reversal of the magnetic texture.



Vorticities of spin current vector fields in reciprocal space. (a) The irrotational source field has zero vorticity. (b) The quadrupolar field has locally nonzero vorticity but zero integral. (c) A general vortex with vorticity of varying sign.

We unveil the origin of the MSHE and connect it to the spin current vorticity, i.e., to the tendency of the spin current to rotate, shear or curve in reciprocal space [3] (see figure). This suggests the following illustrative explanation: Magnetic materials feature spin current whirlpools (or vortices) in reciprocal space for each of the three spin directions. Similar to water whirlpools (in real space), whose handedness leads to an asymmetric deflection of plane water waves, the spin current whirlpools (in reciprocal space) cause an asymmetric deflection of the respective spin components.

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Spin-Orbit Torque MRAM for ultrafast embedded memories: from fundamentals to large scale technology integration and future challenges

Kevin Garello[1]

[1] *imec, Leuven, Belgium*

Microelectronics industry is facing major challenges related to the volatility of CMOS cache memory elements (usually SRAM and eDRAM). Due to decreasing devices size, leakage current in standby mode are now dominating the power dissipation of CMOS circuits. Furthermore, the increased density and reduction in die area lead to heat dissipation and reliability issues. Magnetic RAM (MRAMs) and Spin-Transfer-Torque MRAM (STT-MRAM) are among most credible non-volatile memories candidates that are scalable, low power and with relatively low access times, as well as a compatibility with scaled CMOS processes and voltages. In fact, past years have seen major foundries and tool suppliers investing significant R&D resources into embedded STT-MRAM. They recently started prototyping demonstrators, progressively maturing for mass production of NV embedded memories. Despite all these advantages, STT-MRAM also faces several challenges: i. the write process is still relatively inefficient and long compared to SRAM, ii. speed gain requires to increase current flowing through the bit cell - magnetic tunnel junction (MTJ) – which imposes a severe stress and leads to a reduced endurance of the device and increased error rates. Today, this limits the use of STT-MRAM for eFlash and MCU replacements in caches memories. Spin-Orbit Torque (SOT) is an alternative spin current source originating from the spin-orbit interaction and mediated by Spin Hall and Rashba effects. SOT distinguishes by offering the possibility to switch magnetization using in-plane currents, unlike STT that requires a current flow in the perpendicular direction through MTJ. Such new memory class, SOT-MRAM, promise to mitigate some of the above issues: it is a three terminal MTJ-based concept that allows isolating the read and the write path. It results in significant improvement of the read stability, the write speed and the endurance of the device; therefore opening the path to address SRAM replacement in lowest cache level by MRAM. Across the presentation, I will present our recent development to build and integrate SOT-MTJ cells following industrial processes, using Imec's 300mm platform. After reviewing some key physics involved and material developments, I will describe our first successful integration scheme of SOT-MTJ cells on 300 mm wafers using CMOS-compatible processes. In a second part I will introduce our recent breakthrough field-free switching SOT-MRAM concept that is integration friendly and allows for separate optimization of the field component and SOT/MTJ stack properties, opening a new area for MRAM technology development. Finally, I will discuss some of our recent progress to bring SOT-MRAM toward industrial compatibility.

Electrical manipulation and detection of magnetic insulators with perpendicular anisotropy

Can Onur AVCI

Department of Materials, ETH Zürich, CH-8093 Zürich, Switzerland

Ferrimagnetic insulators possess remarkable properties such as low damping, long magnon propagation, and high structural quality, providing a suitable playground for spintronics research and applications. Recently, robust perpendicular magnetic anisotropy is obtained in ferrimagnetic thulium, europium, and terbium iron garnets down to a few nm thicknesses [1]. By using the spin Hall effect in Pt overlayers, we have demonstrated efficient spin current injection through the TmIG/Pt interface, strong enough to achieve magnetization switching of TmIG(~10nm) with efficiencies comparable to or exceeding that of, e.g., Pt/Co(~1nm) [2]. We then investigated the magnetic texture and current-driven dynamics of domain walls in this system. We found that the domain walls can be efficiently moved using electrical currents in the absence of external fields, indicating the presence of homochiral Néel-type domain walls. Further analysis revealed that these chiral domain walls are stabilized due to the Dzyaloshinkii-Moriya interaction at the substrate/TmIG interface. We found that the domain walls can be propelled faster than 800 m/s per current densities as low as $\sim 10^{12}$ A/m^2, one of the highest reported in any ferromagnetic system thus far [3]. Finally, we discuss a new thermoelectric effect that we have recently discovered, which allows electrical detection of the out-of-plane magnetization component in magnetic insulators in a nonlocal device. The effect relies on efficient spin pumping and spin drag, respectively driven by out-of-plane and in-plane temperature gradients generated by a single heater source. We measure inverse spin Hall effect voltage in Pt, orthogonal to both the ferrimagnetic insulator magnetization vector and the in-plane temperature gradient, to which we coin the name 'thermal spin drag', highlighting its origins.

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Controlling magnon transport in ferrimagnetic insulators

Hans Huebl[1]

[1] *Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany*

Pure spin currents or magnon transport in magnetic insulators are actively discussed in the field of information processing. In this context, one has to differentiate between two transport modes, i.e. the coherent or wave-like magnon transport and the incoherent or diffusive regime. The latter shows similarities to diffusive transport processes known from electrons or phonons triggering the question, whether and how the transport of magnons can be controlled in a potential device.

Here, I will present our recent experiments on the control of magnon spin currents using a device with a magnon injector, detector, and modulator sharing conceptual similarities with a transistor. I will discuss the ability to control the magnon transport using the modulator and discuss possible microscopic explanations. For the injection and detection of magnons we employ spin Hall physics, thus warranting the question which materials are best suited for the conversion between magnons and charges. I will compare the ferromagnetic CoFe alloy to the ubiquitous heavy metal Pt used in many of the experiments.

Electrical and optical manipulation of magnetic skyrmions and chiral domain walls

Felix Büttner[1]

[1] *Massachusetts Institute of Technology, Cambridge, MA, USA*

Skyrmions and chiral domain walls are two- and one-dimensional magnetic solitons, respectively. Both can be realized at room temperature in thin film magnetic materials with functional interfaces with strong spin-orbit coupling [1-5]. Both solitons can be described as quasi-particles with intriguing dynamics, including skyrmion gyration [1], inertia [1], the skyrmion Hall effect [2], topological damping [3], sub-ns switching [4], and ultra-fast motion [5]. These quasi-particles are also promising candidates for several data storage and data processing technologies. In this context, fast and energy efficient operation is key. Here, I will discuss several ways of nucleating and driving magnetic skyrmions and chiral domain walls efficiently by ultrafast electrical and optical stimuli and how these dynamics can be observed via high resolution x-ray imaging. These results will be discussed from a theoretical and experimental perspective.

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Phase-resolved imaging of non-linear spin-wave generation at low magnetic bias field

R. Dreyer[1], C. Körner[1], N. Liebing[1] and G. Woltersdorf[1]

[1]*Martin Luther University Halle-Wittenberg, Institute of Physics, Von-Danckelmann-Platz 3, 06120 Halle (Saale), Germany*

Recently it was shown that the prediction of the non-linear spin-wave excitation in the framework of Suhl instability processes is not adequate at low magnetic bias fields. In particular, it was shown by spatially averaged and time-resolved x-ray ferromagnetic resonance spectroscopy that in the low field regime non-linear spin waves are excited parametrically at 3/2 of the excitation frequency [1].

Here we demonstrate the 3/2 ω non-linear spin-wave (NLSW) generation in $Ni_{80}Fe_{20}$ microstructures using scanning phase-resolved magneto-optical microscopy. For this purpose we have developed a novel variant of scanning magneto-optical microscopy which we term super-Nyquist sampling microscopy (SNS-MOKE) [2]. This technique allows for phase-resolved imaging of the sample at multiple arbitrary frequencies at the same time. In this way we detect the parametrically excited NLSWs at 3/2 of the excitation frequency in space and time directly.

For this type of non-linearities we determine the threshold rf-field for different sample geometries and investigate the phase stability of the NLSW generation as a function of rf-field and bias field. Above the threshold the corresponding wave vectors obtained from the 2D-FFT of the observed spatially resolved spin-wave pattern at 3/2 ω are in agreement with the theoretical predictions from Bauer et al. [1].

Our results are further supported by micro-focus Brillouin light scattering (μBLS) experiments performed on the same samples.

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Abstracts of Posters

(in alphabetical order)

FIB written artificial Skyrmion Bubble lattices in Pt/Co/HM-Multilayers

Valentin Ahrens[1], S. Mendisch[1], W.Kaiser[2], M. Kiechle[1] and Markus Becherer[1]

Technische Universität München (TUM),
[1]Chair of Nanoelectronics
[2] Simulation of Nanosystems for Energy Conversion
Munich, Germany

Skyrmions prove an enormous potential as information carrier for data storage and processing. A promising host material for Skyrmions are magnetron sputtered magnetic thin films as the material properties there are easily accessible via the layers thicknesses, repetitions, materials and order.

As commonly known ion irradiation can be used to tune the properties of magnetic multilayers, e.g. to create artificial nucleation centers for magnetic logic gates. Here we investigate an option to create artificial grids of bubble shaped magnetic domains by FIB irradiation. Therefore thin films exhibiting DMI are irradiated in a hexagonal pattern, reducing anisotropy in the outlines.

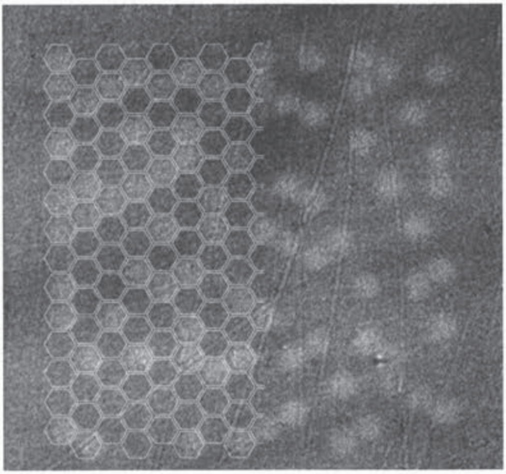

Figure 1. Widefield-MOKE imaging of the Formation of Skyrmion Bubbles in an FIB irradiated multilayer of Pt/Co/Ir. The irradiated honeycomb pattern is shown in light grey.

Simulations of such structures have shown that the domain inside such an irradiated region resembles a Skyrmion. However due to the relatively large size (> 100 nm) we name the domains skyrmion bubbles.

The presented method has proven to be scalable and the structures are stable at room temperature and zero field, due to the quasi geometrical confinement.

To conclude we have presented a platform that is well suited, to further investigate the properties of Skyrmion bubbles and potentially Skyrmions.

Long range coupling of magnetic bi-layers by coherent phonons

K. An[1], A.N. Litvinenko[1], A.A. Fuad[1], V. V. Naletov[1,2], L. Vila[1], U. Ebels[1], G. de Loubens[3], H. Hurdequint[3], N. Beaulieu[4], J. Ben Youssef[4], N. Vukadinovic[5], G.E.W. Bauer[6], A. N. Slavin[7], V. S. Tiberkevich[7], and O. Klein[1]

[1]*Univ. Grenoble Alpes, CEA, CNRS, Grenoble INP, INAC-Spintec, 38054 Grenoble, France*
[2]*Institute of Physics, Kazan Federal University, Kazan 420008, Russian Federation*
[3]*SPEC, CEA-Saclay, CNRS, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*
[4]*LabSTICC, CNRS, Université de Bretagne Occidentale, 29238 Brest, France*
[5]*Dassault Aviation, Saint-Cloud 92552, France*
[6]*Institute for Materials Research and WPI-AIMR and CSRN, Tohoku University, Sendai 980-8577, Japan*
[7]*Department of Physics, Oakland University, Michigan 48309, USA*

We demonstrate that the spin waves can be strongly coupled to coherent shear waves that have very long characteristic decay length and propagate ballistically over millimetric distances. In our spin valve structure, which consists of two insulating magnetic layers (YIG) deposited on both sides of a dielectric GGG substrate, the standing acoustic waves couple to the magnetization oscillations in both layers. The coupling signifies a change of sign between the acoustic modes with even or odd indices, which results in a contrast between two tones separated by half a wavelength. We measure the contrast at different polar angles via inverse spin Hall effect using a thin Pt wire deposited on one side of the YIG layer. In our sample the two YIG layers resonate at slightly different frequencies. The change in the polar angle allows to detune their resonances and make them cross, which leads to a peak of the contrast at the crossing point. We show that the observed behavior is in agreement with theoretical prediction. This long range coherent coupling by phononic angular momentum currents adds new functionalities to insulator spintronic circuits and devices.

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Surface states and all electrical detection of skyrmions in a chiral magnetic insulator

A. Aqeel[1], M. Azhar[2], N. Vlietstra[1], J. Sahliger[1], H. Hübl[1], B. J. van Wees[2], T. T. M. Palstra[3], M. Mostovoy[2], C. H. Back[1]

[1]*Technische Universität Munich*

[2]*Zernike Institute for advanced Materials, University of Groningen, The Netherlands*

[3]*University of Twente, The Netherlands*

In chiral magnets, the Dzyaloshinskii Moriya interaction leads to complex magnetic orders such as the skyrmion crystal [1], spiral, and collinear states. Our numerical and analytical calculations show that for chiral magnets, the magnetism on the surface is very different from that in the bulk. Furthermore, the surface magnetization differs greatly for various phases in the phase diagram, thus having implications for surface-sensitive measurable quantities such as the spin Hall magneto-resistance [2]. Our experimental results for Cu2OSeO3 confirm that magnetism in chiral magnetic insulators can be effectively measured by applying an electric current [3]. This all-electric readout is important for the reduction of power consumption in future spintronics applications.

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REXS-FMR: a novel method for the determination of dynamic modes in complex magnetic materials

S. Pöllath[1], A. Aqeel[2], A. Bauer[2], C. Luo[3], H. Ryll[3], F. Radu[3], C. Pfleiderer[2], G. Woltersdorf[4], C.H. Back[2,5]

[1]Institut für Experimentelle Physik, Universität Regensburg, D-93040 Regensburg, Germany
[2]Physik-Department, Technische Universität München, D-85748 Garching, Germany
[3]Helmholtz-Zentrum Berlin für Materialien and Energie, D-12489 Berlin, Germany
[4]Institut für Physik, Universität Halle-Wittenberg, D-06120 Halle (Saale)
[5]Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München

Cubic chiral magnets, such as Cu_2OSeO_3, exhibit a variety of non-collinear spin textures including a trigonal lattice of spin whirls, so-called skyrmions. Using magnetic resonant elastic x-ray scattering on a crystalline Bragg peak and its magnetic satellites while exciting the sample with magnetic fields at GHz frequencies, we probe the ferromagnetic resonance modes of these spin textures by means of the scattered intensity. Most notably, the three eigenmodes of the skyrmion lattice are detected with large sensitivity [1]. As this novel technique, which we label REXS-FMR, is carried out at distinct positions in reciprocal space, it allows to distinguish contributions originating from different magnetic states, providing information on the precise character, weight and mode mixing as a prerequisite of tailored excitations for applications.

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Interfacial Dzyaloshinskii-Moriya interaction and chiral magnetic textures in a ferrimagnetic insulator

S. Ding[1,2,3], A. Ross[2,3], R. Lebrun[2], S. Becker[2], K. Lee[2], I. Boventer[2,4], S. Das[2,3], Y. Kurokawa[2,5], S. Gupta[2], J. Yang[1,6,7], G. Jakob[2,3] and M. Kläui[2,3,8]

[1]State Key Laboratory for Mesoscopic Physics, School of Physics, Beijing, China
[2]Institute of Physics, Johannes Gutenberg-University Mainz, Mainz, Germany
[3]Graduate School of Excellence Materials Science in Mainz, Mainz, Germany
[4]Institute of Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany
[5]Graduate School of Information Science and Electrical Engineering, Fukuoka, Japan
[6]Collaborative Innovation Center of Quantum Matter, Beijing, China
[7]Beijing Key Laboratory for Magnetoelectric Materials and Devices, Beijing, China
[8]Center for Quantum Spintronics, Department of Physics, Trondheim, Norway

Insulating rare earth iron garnets (RIG) have drawn great interest in recent years due to their excellent performance in the field of spintronics. However, for device applications, one would need a combination of stable spin structures and efficient electrical manipulation and both can be achieved by spin-orbit effects so that the combination is often termed spin-orbitronics. To obtain stable spin structures, chiral exchange interactions, such as the Dzyaloshinskii-Moriya interaction (DMI) can be employed. In ultra-thin RIG films with perpendicular magnetic anisotropy (PMA) efficient electrical switching [1] was observed. In our work, we grow high quality TmIG and GdIG [2] films by pulsed laser deposition. We first study the chiral DMI induced in GGG/TmIG/Pt heterostructures [3]. We find a clear scaling of the DMI with the inverse of the TmIG layer thickness, which demonstrates the interfacial origin of the DMI [3]. We find a surprisingly long decay length so that we can obtain sizeable DMI in insulating TmIG even in >10 nm thick films, which is an order of magnitude larger than found for metallic systems. By direct imaging, we find skyrmions and chiral domain walls and we identify the GGG/TmIG interface as the main source of the DMI. As the second step, we then manipulate the magnetization and in particular the chiral spin structures by spin-orbit torques. We find that we can move the spin structures all synchronously confirming their chiral nature. Furthermore, switching of single domain particles is achieved for low current densities, down to $2.8 \cdot 10^{10}$ A/m^2. So overall, we demonstrate that in insulating ferrimagnet based devices the key spin-orbit effects, namely chiral exchange interactions stabilizing skyrmions and efficient spin-orbit torques can be realized thus opening the field of insulator spin-orbitronics.

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Ultrafast spin dynamics in antiferromagnetic Mn_2Au

Yannic Behovits[1,2], Alexander Chekhov[1,2], Lukas Nadvornik[1,2], Julius Heitz[1,2], S. Yu. Bodnar[3], Martin Wolf[2], Martin Jourdan[3], Mathias Kläui[3] and Tobias Kampfrath[1,2]

[1]*Department of Physics, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany*

[2]*Department of Physical Chemistry, Fritz Haber Institute of the Max Planck Society, Faradayweg 4-6, 14195 Berlin, Germany*

[3]*Institut für Physik, Johannes Gutenberg-Universität, Staudinger Weg 7, 55128, Mainz, Germany*

In antiferromagnets, the intrinsic terahertz (THz) magnon resonances are expected to enable pathways to high-speed spin information processing. In certain non-centrosymmetric antiferromagnetic materials such as semimetallic CuMnAs or metallic Mn_2Au, switching of the antiferromagnetic Neél vector has recently been demonstrated by using pulsed electrical currents in both materials [1,2], and by free-space THz pulses in the case of CuMnAs [3]. However, the exact mechanism and the timescale of this switching behavior still remain elusive. It is therefore important to understand in detail the spin dynamics in these materials.

Here, we investigate spin dynamics in the perturbative regime in polarized Mn_2Au thin films. A THz single-cycle pulse is used to trigger dynamics whose evolution is monitored by magneto-optical probing. Our measurement scheme allows for the separation of effects which are odd or even with respect to the driving THz field. The odd contribution is found to be linear in the driving field and features a remarkable dependence on the direction of the antiferromagnetic Neél vector. The even contribution, however, shows a strong probe-polarization dependence, thereby indicating a contribution from the Cotton-Mouton effect [4]. A symmetry analysis is applied to clarify the possible origins of the observed effects.

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Biomagnonic logic device concepts: A new approach to spintronics?

T. Feggeler[1], B. Zingsem[1,2], R. Meckenstock[1], M. Winklhofer[3], D. Spoddig[1], H. Ohldag[4], M. Farle[1], H. Wende[1] and K. Ollefs[1]

[1]*Faculty of Physics and CENIDE, University Duisburg-Essen, Lotharstr. 1, 47057 Duisburg, Germany*

[2]*Ernst Ruska Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*

[3]*School of Mathematics and Science, University of Oldenburg, 26129 Oldenburg,Germany*

[4]*Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA, United States*

Magnetotactic bacteria open a pathway to biomagnonic logic devices enabling a new approach in spintronics [1]. By tailoring the arrangement of the nanoparticle chains inside these bacteria, magnon based logic devices are possible. Here, we present concepts of biomagnonic logic devices of single nanoparticle chains in wild type and genetically modified magnetotactic bacteria by means of Ferromagnetic Resonance (FMR) and micromagnetic simulations. The angular dependent FMR measurements show that the dipolar coupled nanoparticles exhibit complex inter-particle and inter-chain-segment phase relationships, leading to band gaps and band deformations, strongly depending on the particle arrangement. Micromagnetic simulations reveal a dynamic behavior which may be exploited for future magnonic devices. A complementary experimental technique to localize the origin of resonant responses in such nano particle ensembles is Scanning Transmission X-Ray Microscopy detected Ferromagnetic Resonance (STXM-FMR) [2], enabling the element specific and time resolved investigation of nanoparticles with a spatial resolution < 50 nm. The first result for a single magnetosome chain is presented.

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Chiral magnetic texture and spin dynamics in magnetic superlattices

Luis Flacke[a,b], Valentin Ahrens[c], Simon Mendisch[c], Kiechle Martina[c], Becherer Markus[c] Lukas Liensberger[a,b], Matthias Althammer[a,b], Hans Huebl[a,,b,d,e], Stephan Geprägs[a], Rudolf Gross[a,b,d,e], Mathias Weiler[a,b]

[a] Walther-Meißner Institut, Bayerische Akademie der Wissenschaften, Garching, Germany
[b] Physics Department, Technical University of Munich, Garching, Germany
[c] Chair of Nanoelectronics, Technical University of Munich, Munich, Germany
[d] Nanosystems Initiative Munich, Munich, Germany
[e] Munich Center for Quantum Science and Technology (MCQST), Munich, Germany

Chiral magnetic textures, in particular magnetic skyrmions, are attractive for data storage and processing via magnetic "racetracks" [1] and logic gates [2]. These textures may also be used as neurotransmitters in artificial neural networks [3], and even for quantum computing [4]. For such applications, thin-film, all-metallic magnetic heterostructures with chiral texture stabilized by interfacial Dzyaloshinskii-Moriya interaction (iDMI) are ideal.

Here, we investigate magnetic superlattices based on the low-damping and high saturation magnetization binary alloy $Co_{25}Fe_{75}$ (CoFe) [5,6]. We taylor the iDMI and interfacial perpendicular magnetic anisotropy by varying Pt, CoFe, and Ir layer thicknesses in Pt/CoFe/Ir heterostructures. After optimization of the multilayer system we detect the dynamic response of chiral magnetic texture via broadband FMR. The formation of chiral magnetic texture is confirmed by magnetic force microscopy and SQUID magnetometry measurements.

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Reflection-less width-modulated magnonic crystals

Pascal Frey,[1] Aleksei A. Nikitin,[2] Dmytro A. Bozhko,[1,] Sergey A. Bunyaev,[3] Gleb N. Kakazei,[3]
Alexey B. Ustinov,[2] Boris A. Kalinikos,[2] Florin Ciubotaru,[4] Andrii V. Chumak,[1]
Qi Wang,[1] Vasyl S. Tiberkevich,[5] Burkard Hillebrands,[1] and Alexander A. Serga[1]

[1]Fachbereich Physik and Landesforschungszentrum OPTIMAS,
Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
[2]Department of Physical Electronics and Technology,
St. Petersburg Electrotechnical University, 197376 St. Petersburg, Russia
[4]IFIMUP and IN-Institute of Nanoscience and Nanotechnology,
Departamento de Fisica, Universidade do Porto, 4169-007 Porto, Portugal
[4]imec, B-3001 Leuven, Belgium
[5]Department of Physics, Oakland University, Rochester MI 48309, United States

Magnonic crystals receive a lot of attention in spintronics, due to their great potential for information processing technologies [1]. The main features of these crystals are the presence of bandgaps in the spin-wave spectra. The bandgaps are formed due to the Bragg reflections on the artificially created periodic structures. Therefore, it is possible to influence the properties of the crystals using different designs of these structures within a magnetic material. Recently, potential of edge- and width-modulated waveguiding structures for creation of macro- and micro-sized magnonic crystals was demonstrated [2,3].

In this work, we studied spin-wave propagation in longitudinally magnetized width-modulated yttrium-iron-garnet (YIG) waveguides by means of both Brillouin light scattering and microwave spectroscopies. The waveguides were produced by chemical etching of a YIG film of 8.5 µm-thickness. Short pulses (30 ns) of backward volume magnetostatic spin waves (BVMSW) were excited, close to the ferromagnetic resonance frequency and their propagation was visualized and measured, both in pass and rejection frequency bands. We found, that the width-modulated magnonic crystal, shows a new underlying mechanism, where no back reflection of the spin-wave pulse is observed. Such a reflection-less magnonic crystal is a promising candidate for the realization of frequency selective or multi-component devices.

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Current-induced orbital angular momentum and orbital torque for spin-orbitronics

Dongwook Go[1,2,3], Jan-Philipp Hanke[1], Frank Freimuth[1], Stefan Blügel[1], Yuriy Mokrousov[1,4], and Hyun-Woo Lee[2]

[1]*Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA,52425 Jülich, Germany*

[2]*Department of Physics, Pohang University of Science and Technology, Pohang 37673, Korea*

[3]*Basic Science Research Institute, Pohang University of Science and Technology, Pohang 37673, Korea*

[4]*Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany*

Spin-orbit torque (SOT) plays a central role in many spin-orbitronic phenomena, such as current-induced magnetization switching and domain wall motion. It has been regarded that spin Hall effect and Rashba effect are dominant underlying mechanisms of the SOT, both of which results in the spin accumulation at the interface between a nonmagnet and ferromagnet. Recently, we proposed orbital analogues of these phenomena, called orbital Hall effect [1] and orbital Rashba effect [2], as ways to electrically generate orbital angular momentum. These can be understood as parental effects to the spin Hall effect and Rashba effect, which occurs regardless of the spin-orbit coupling, and the spin effects follow the orbital effects by the spin-orbit coupling.

In this presentation, we show that there exists an additional channel for the SOT generation through the orbital degree of freedom. When the orbital current is injected to a ferromagnet, it transfers the angular momentum and induces a torque to the magnetization. We call this orbital torque [3], analogous to spin torque caused by the spin-transfer mechanism. We found that SOT generation from the orbital channel can be of comparable magnitude as the SOT generation from the spin channel. The orbital torque and spin torque can be added up or cancel each other depending on material combinations, resulting in larger or smaller torque, respectively. This not only provides a way to enhance the torque efficiency, but also widens material choices since current-induced orbital angular momentum does not require heavy elements with large spin-orbit coupling. We discuss experimental implications briefly.

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Magnon transport in three-terminal magnetically ordered insulator/platinum nanostructures

J. Gückelhorn[1,2], T. Wimmer[1,2], S. Regmi[3], A. Gupta[3], S. Geprägs[1], M. Weiler[1,2], H. Huebl[1,2,4,5], R. Gross[1,2,4,5] and M. Althammer[1,2]

[1]*Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany*

[2]*Physik-Department, Technische Universität München, 85748 Garching, Germany*

[3]*University of Alabama, Center for Materials for Information Technology MINT and Department of Chemistry, Tuscaloosa,AL 35487 USA*

[4]*Nanosystems Initiative Munich (NIM), Schellingstraße 4, 80799 München, Germany*

[5]*Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, 80799 München, Germany*

In modern day information technology, we gradually approach the technological limits of devices based on electron transport. Thus, it is imperative to explore novel routes for information processing. One route is the transport of information via spin waves (magnons) in magnetically ordered insulators (MOIs). To this end, we investigate heterostructures consisting of spin-orbit coupled metals and magnetically ordered insulators, which allow us to study pure spin current transport by all-electrical means. Utilizing the spin Hall effect and the inverse spin Hall effect in the metal allows to transform a charge current into a pure spin current and vice versa. This enables an all-electrical generation and detection of pure spin currents in such heterostructures.

We present our recent results of the transport of magnons in the ferrimagnetic insulator (FMI) materials nickel ferrite ($NiFe_2O_4$), and yttrium iron garnet ($Y_3Fe_5O_{12}$). In our experiments, we deposit three electrically isolated platinum (Pt) electrodes on top of our FMI thin films. Driving a charge current through the first Pt strip, a pure spin current is injected into the FMI layer. The excited magnons diffuse and can be detected at the third Pt electrode. The center strip, the modulator, between these two strips acts as an additional injector for pure spin currents and enables electrical control of the diffusive magnon transport. We compare the properties of the magnon transport in NFO, and YIG, and compare these results to spin Hall magnetoresistance measurements.

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Impact of the interface on ultrafast spin-to-charge conversion in metallic bilayers

Oliver Gueckstock[1,2], Lukáš Nádvorník[1,2], Martin Gradhand[3], Tom Seifert[1,2,4], Genaro Bierhance[2], Martin Wolf[1], Mehran Vafaee[5], Joel Cramer[5], Gerhard Jakob[5], Mathias Kläui[5] and Tobias Kampfrath[1,2]

[1]*Department of Physics, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany*
[2]*Department of Physical Chemistry, Fritz Haber Institute of the Max Planck Society, Faradayweg 4-6, 14195 Berlin, Germany*
[3]*School of Physics, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK*
[4]*Department of Materials, ETH Zürich, Hönggerbergring 64, 8093 Zürich, Switzerland*
[5]*Institute of Physics, Johannes-Gutenberg Universität Mainz, Staudinger Weg 7, 55128 Mainz, Germany*

The efficient conversion of spin to charge currents by spin-orbit interaction (SOI) is of great relevance for the detection and generation of spin currents in future spin-based electronics [1] and the development of efficient emitters of terahertz electromagnetic pulses [2,3]. Thus, understanding and optimization of spin-to-charge conversion (S2C) is highly desirable. Current research has started taking the role of interfaces into consideration. For example, recent works demonstrated ultrafast S2C by the inverse Rashba-Edelstein effect at interfaces of metallic heterostructures [4,5]. Here, we analyze S2C in an important model system: F|N bilayers consisting of ferromagnetic (F) and nonmagnetic (N) metal thin films. To measure S2C, we employ femtosecond optical pulses to trigger ultrafast spin transport from the F into the N layer (see figure) [2-5]. Through S2C, the spin current is partially converted into a transverse charge current that is monitored by detecting the concomitantly emitted THz electromagnetic radiation. To simplify the separation of interfacial S2C, we minimize S2C in the N bulk by using the common low-SOI materials Al and Cu. Our measurements indicate that S2C at Co|Al and Py|Cu interfaces can, respectively, even become comparable to the overall S2C in Co|Pt and Py|Pt reference bilayers. We show that S2C is drastically affected by modification of the interface and discuss our results in terms of possible extrinsic S2C mechanisms.

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Growth and Characterization of YIG nano-films grown by metal-organic aerosol deposition.

Christopher Heins[1], Robert Gruhl[1], Vasily Moshnyaga[1] and Henning Ulrichs[1]

[1]I. Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Yttrium iron garnet (YIG) is a popular ferromagnetic insulator due to its ultra-low magnetic damping. Thereby, it is well suited to study fundamental physics like magnon Bose-Einstein condensation, and is a prominent material for magnon spintronic applications. While liquid phase epitaxy methods allow since many decades to grow YIG films with micrometer thickness, nowadays pulsed laser deposited (PLD) YIG films with thicknesses of few nanometers are in the scientific focus. On this poster we report on such YIG nano-films, which were grown by metal-organic aerosol deposition (MAD) as an alternative approach. This method allows to synthesize complex oxide films directly from its atomic constituents. Besides characterization of structural and magnetic properties by XRD and SQUID, we use a custom-built stripline Ferromagnetic Resonance setup to determine dynamic magnetic properties. We find a Gilbert damping of about $(13\pm9)\cdot10^{-4}$, which is comparable with typical PLD grown films.

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Topological spin structures in a ferromagnetic monolayer

Boris Seng[1,2,3,4], Daniel Schönke[1], Nico Kerber[1,3,4], Fabian Kammerbauer[1], Jean-Loïs Bello[2], Daniel Lacour[2], Michel Hehn, Robert Reeve[1,3], Stéphane Mangin[2], and Mathias Kläui[1,3,4]

[1]*Institut für Physik, Johannes Gutenberg Universität Mainz, 55099 Mainz, Germany*
[2] *Institut Jean Lamour, UMR CNRS 7198, Université de Lorraine, 54506 Vanoevre-lès-Nancy, France*
[3] *Graduate School of Excellence Materials Science in Mainz, 55128 Mainz, Germany*
[4] *Max Planck Graduate Center, DE-55128 Mainz, Germany*

Magnetic skyrmions are topologically protected spin textures particularly suitable for next generation spintronics devices, like the skyrmion-based racetrack memory [1]. Studies have confirmed the possibility for current-driven skyrmion dynamics in ultrathin ferromagnets [2]. However, the topological Magnus effect leads to a transverse motion of ferromagnetic skyrmions due to their non-zero topological charge [2].

Antiferromagnetically exchange-coupled skyrmions or compensated ferrimagnets could suppress this effect owing to an overall zero topological charge. Recently, a reduced skyrmion Hall angle was observed in GdCoFe-based ferrimagnetic material [3]. Furthermore, ultrafast chiral structure dynamics is predicted at the angular momentum compensation temperature in ferrimagnetic and antiferromagnetic materials [4]. However, experimental results showing skyrmion motion with a near zero skyrmion Hall angle have been elusive so far.

In this work, we report as a first step the observation of homochiral pure Néel skyrmions in GdFeCo-based multilayers stabilized by a strong interfacial Dzyaloshinskii-Moriya interaction. We show the stabilization of these textures over a wide range of temperature making it interesting for future spintronic devices.

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Theory and simulation on nonlinear spin-wave dynamics in magnetic vortices

L. Körber[1,2], K. Schultheiss[1], T. Hula[1,3], R. Verba[4], A. Kákay[1], T. Hache[1,3], H. Schultheiss[1,2]

[1]Helmholtz-Zentrum Dresden–Rossendorf, Institute of Ion Beam Physics and Materials Research, Bautzner Landstraße 400, 01328 Dresden, Germany

[2]Technische Universität Dresden, 01062 Dresden, Germany

[3]Institut für Physik, Technische Universität Chemnitz, 09107 Chemnitz, Germany

[4]Institute ofMagnetism, National Academy of Sciences of Ukraine, Kyiv 03680, Ukraine

One of the fascinating qualities of spin waves (or magnons), which are the elementary excitations in magnetically ordered substances, is their nonlinear behavior at moder- ate excitation powers. This makes spin waves not only an attractive model system to study general nonlinear systems, but it also provides a way to utilize nonlinear dynamics in possible technical applications. In a ferromagnetic nano disk which is magnetized in the vortex state, the spin-wave modes meet strict boundary conditions and therefore inherit a discrete spectrum. When driven with a large enough excitation field, they can decay into other spin-wave modes within well-defined channels due to a nonlinear process called three-magnon scattering [1]. The aim of this project is to explore this phenomenon within nonlinear spin-wave theory and by means of micromagnetic simulations.

For this purpose, first the linear dynamics are mapped out and the possible scattering channels are predicted. The stability of these channels with respect to static external fields is studied. Within this context, exotic spin-wave modes which arise in a broken cylindrical symmetry are found. Moreover, a model to predict the temporal evolution of the spin-wave modes is developed within the classical Hamiltonian formalism for nonlinear spin-wave dynamics. Together with micromagnetic simulations, this model is applied in order to study the power-dependence of three-magnon scattering as well as to uncover a phenomenon called stimulated three-magnon scattering, which may allow for an integration of this nonlinear pro- cess in magnonics circuits. The results are compared with Brillouin light-scattering experiments which were conducted prior to this thesis or were motivated by it. Financial support of within DFG programme SCHU 2922/1-1 and KA 5069/1-1 is acknowledged.

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Spin-orbit torque effect in the surface of Bi_2Te_3 doped with magnetic transition-metal defects

A. Kosma[1], P. Rüßmann[2], S. Blügel[2], and P. Mavropoulos[1]

[1]Department of Physics, National and Kapodistrian University of Athens, Panepistimioupolis 15784 Athens, Greece
[2]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

This work comprises a theoretical and computational investigation of the phenomenon of the spin-orbit torque [1] in topological insulators [2]. In particular, we present the spin-orbit torque exerted on the magnetic moments of transition-metal atoms (Cr, Mn, Fe, and Co) that are embedded in the surface of the topological insulator Bi_2Te_3, in response to an electrical current in the surface. The multiple scattering problem is solved by first-principles calculations within the full-potential relativistic Korringa-Kohn-Rostoker (KKR) Green function method, while the spin-orbit torque calculations are carried out combining the KKR method with the semiclassical Boltzmann transport equation [3]. We discuss the correlation of the spin-orbit torque to the charge and spin current on the Fermi surface, analyzing the spin accumulation and the spin flux contribution to the spin-orbit torque on the defects. The effect of resonant scattering is discussed, interpreting the results of different defects systems. In addition, we present the resistivity and the Joule heat production in these systems. Finally, we find that the special characteristics of the studied system, i.e., the metallic surface states and the perpendicular spin-polarization of the surface electrons with respect to the magnetization of defects, reinforce the spin-orbit torque effect. Consequently, these systems are promising for spintronic applications.

This work was supported by computational time granted from the GRNET in the National HPC facility - ARIS - under project ID pr007039-TopMagX.

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Spin-Hall Nano-oscillators, optimized shape and fabrication strategies

Stephanie Lake[1], Philipp Dürrenfeld[1], Frank Heyroth[2], and Georg Schmidt[1,2]

[1]Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, 06120 Halle, Germany

[2]Interdisziplinäres Zentrum für Materialwissenschaften, Martin-Luther-Universität Halle-Wittenberg, 06120 Halle, Germany

Harnessing auto-oscillations of magnetization produced by the spin Hall effect (SHE) paves way for novel exploration of spintronic physics. Spin Hall nano-oscillators (SHNOs), typically a bilayer device comprised of a heavy metal such as Pt and thin film of ferromagnetic material (FM), exhibit auto-oscillations when spin transfer torque cancels out the damping torque applied on magnetization precession.

Several publications focused on Py-based SHNOs with nanoconstrictions (NCs) show that HF electrical signals can be generated during auto-oscillation by taking advantage of the anisotropic magnetoresistance (AMR) effect in Py[1, 2]. However, practical use of these HF signals is challenging due to their low power[2]. To increase power, one can improve auto-oscillations in SHNOs by manipulating its geometry and material parameters.

This work concentrates on a systematic investigation of Py-based SHNOs fabricated using different electron beam lithography (EBL) strategies. The work includes a detailed investigation of different resists and exposure strategies in order to optimize shape and size of the constriction. We also show simulations of the static field within NCs for geometries that are possible to pattern with EBL and subsequent fabrication attempts of these geometries to test their viability. Furthermore, I obtain the AMR ratio and Gilbert damping constant using AMR measurements and ferromagnetic resonance, respectively. Understanding how EBL affects SHNO characteristics will allow for future optimization.

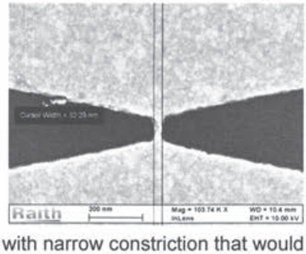

Fig. 1. Proof of concept device with narrow constriction that would support a large charge current density in a SHNO. Consequently, relatively large spin current density is transferred into the FM.

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Periodical magnetic wire width modulation for reliable domain wall propagation in sensor applications

O. Lozhkina[1], **R. Reeve**[1], **G. Jakob**[1] **and M. Kläui**[1]

[1]*Johannes Gutenberg University, Mainz, Germany*

Magnetic domain wall (DW) propagation in confined structures under an applied field can reach speeds of hundreds of m/s and is of a great interest for non-volatile logic and memory devices, as well as magnetic sensors [1-2]. While the first multiturn sensor based on field-driven DW motion in a looping wire is commercially available [1], a crucial problem of such sensors is the high stochasticity of the DW pinning/depinning behaviour, which limits the DW propagation and determines sensor robustness. Nevertheless, it was shown that special approaches to the design and composition of a wire drastically affect the DW motion, providing a route to achieving reliable DW propagation. A periodic wire width modulation has been predicted to conserve the DW spin structure in order to maintain fast and deterministic propagation. Here we perform a thorough micromagnetic simulation study in order to understand the mechanism of DW propagation in Py wires via fields and determine the dependence of the DW spin structure transformation on the geometry. The DW motion, depinning and nucleation processes are studied within a wide range of width modulation periods and amplitudes.

Our simulations show that the lateral distance for DW transformation (Walker period) gradually decreases with increasing field and tends to a certain limit depending on the wire cross-section. Introducing modulation leads to a rise in the propagation field and a drop in the nucleation field but greatly increases the Walker field and with proper period and amplitude fully suppresses the Walker Breakdown, conserving the DW spin structure. Through careful e-beam lithography, corresponding Py wires with modulated width are fabricated for experimental investigation of the effects.

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Chirality-induced linear response properties in hexagonal Mn_3Ge

S. Mankovsky, S. Wimmer, and H. Ebert

Dept. Chemistry/Phys. Chemistry, LMU Munich, Munich, Germany

Taking the non-collinear antiferromagnetic hexagonal Heusler compound Mn_3Ge as a reference system, the contributions to linear response phenomena arising solely from the chiral coplanar and non-coplanar spin configurations are investigated in first-principles calculations. Orbital moments, X-ray absorption, anomalous and spin Hall effects, as well as corresponding spin-orbit torques and Edelstein polarizations are studied depending on a continuous variation of the polar angle relative to the Kagome planes of corner-sharing triangles between the non-collinear antiferromagnetic and the ferromagnetic limits. By scaling the speed of light from the relativistic Dirac case to the non-relativistic limit the chirality-induced or topological contributions can be identified by suppressing the spin-orbit coupling.

Current induced chiral domain wall motion by spin-orbit torques in CuIr/CoFeB/MgO thin films

Franziska Martin,[1] Joel Cramer,[1,2] Kyujoon Lee,[1] Tom Seifert,[3] Alexander Kronenberg,[1] Felix Fuhrmann,[1] Gerhard Jakob,[1] Martin Jourdan,[1] Tobias Kampfrath,[3,4] and Mathias Kläui[1,2]

[1]Institute of Physics, Johannes Gutenberg-University Mainz, 55099 Mainz, Germany
[2]Graduate School of Excellence Materials Science in Mainz, 55128 Mainz, Germany
[3]Department of Physical Chemistry, Fritz Haber Institute of the Max Planck Society, 14195 Berlin, Germany

[4]Department of Physics, Freie Universität Berlin, 14195 Berlin, Germany
E-mail: f.martin@students.uni-mainz.de

The use of thin films in magnetic storage devices requires suitable materials that enable for instance ultra-fast and low-power domain wall motion. Research in the recent years has shown that trilayers consisting of a heavy metal (HM), ferromagnet and oxide layer are promising systems for spintronic applications [1]. In these, the combination of large spin-orbit torques (SOTs) and chiral Néel domain walls due to the Dzyaloshinskii-Moriya interaction (DMI) allows for fast domain wall motion. The DMI that is an antisymmetric exchange interaction favors the formation of chiral magnetic textures that efficiently can be manipulated by SOTs [1].
While so far Pt has been used as the archetypical HM layer, we have recently identified CuIr alloys with strong spin-orbit coupling leading to a large spin Hall angle [2]. Using DC spin-Seebeck and AC THz excitations [3], we measure the spin Hall angle in YIG/Cu1-xIrx bi-layers over a wide concentration range ($0.05 \leq x \leq 0.7$) and observe a highly tunable spin Hall angle with a maximum for Ir concentrations around 40%. Consistent results between the DC and THz measurements show that the spin Hall effect is operational at fs timescales [2].
In using this optimal composition in the trilayer Cu60Ir40/CoFeB/MgO we quantify the DMI by current induced domain wall motion and find right-handed chiral domain walls with a Néel component of the wall. We determine the SOTs via a 2nd harmonic experiment. Here we identify a strong angular dependence of the current induced effective fields on the original magnetization direction that needs to be included to understand the dynamics when considering the effective manipulation of spins by current [4].

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Perpendicular Nanomagnetic Logic Based on Low Anisotropy Co\Ni Multilayer

Simon Mendisch[1], Valentin Ahrens[1], Martina Kiechle[1], and Markus Becherer[1]
[1] Chair of Nanoelectronics, Technical University of Munich, Munich, Germany

Perpendicular Nanomagnetic logic is listed as a potential "Beyond-CMOS" candidate in the International Roadmap for Devices and Systems 2017 [1]. PNML thereby utilizes the anti-ferromagnetic dipole coupling of adjacent nanomagnets with perpendicular magnetic anisotropy to achieve complex logic operations [2].

In this work, Cobalt\Nickel multilayers with low perpendicular magnetic anisotropy are optimized for the lowest achievable coercivity while retaining the highest possible total magnetic moment, still supporting single-domain states. This optimization is done to achieve a vital clock-field reduction in nanomagnetic logic devices with perpendicular magnetic anisotropy, enabling highly efficient on-chip field clocking. It is shown that sub 10mT coercivities are achievable utilizing a $Ta_2\backslash Pt_{1.5}\backslash[Co_{0.2}\backslash Ni_{0.4}]_{x8}$ stack in combination with precise manipulation of the anisotropy landscape via local Ga+ ion irradiation, in order to control of the point of nucleation.
Statistical data is used to assess the Ga+ ion dose-dependent coercivity and provide a detailed insight into the overall switching field-distributions. Nanosecond field pulsing is used to assess the time evolution of the nucleation fields, confirmed to be following the Arrhenius model at least down to pulse lengths of 10 ns, resulting in nucleation fields more than twice as high. The obtained findings are then applied to demonstrate the first pNML logic elements fulfilling the requirements for on-chip clocking schemes [3].

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Non-equilibrium spin dynamics and statics enforced by spin currents in nano-YIG films

D. Metternich[1] and H. Ulrichs[1]

[1]*I. Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*

We report on a numerical investigation of spin dynamics and dynamically stabilized non-equilibrium spin-textures in a magnetic thin-film, made of Yttrium-Iron-Garnet (YIG), which is exposed to a small in-plane oriented magnetic field and strong spin currents. Micromagnetic simulations display a rich variety of phenomena, which include dynamic regimes hosting localized, non-propagating solitons, a turbulent chaotic regime, as well as a quasi-static phase featuring a stripe-like magnetization texture, and eventually at largest spin current a homogeneously switched state.

THz spin-wave generation in optically-driven acoustic resonators

Dennis Meyer, Vitaly Bruchmann-Bamberg, Christopher Heins, Vasily Moshnyaga and Henning Ulrichs

I. Physical Institute, Georg-August University Göttingen, 37077 Göttingen, Germany

Ultrafast optically-driven coherent THz spin wave sources are of crucial importance for high frequency spintronic applications. However, a monochromatic coherent spin-wave generation for frequencies $f = 0.1 - 6$ THz is hard to achieve using optical methods, which produce rather incoherent or non-monochromatic spin-waves [1]. Magneto-elastic coupling, usually viewed as an undesirable dissipation channel in spintronics, was recently shown to generate spin currents [2] and coherent magnetic oscillations in the low GHz regime [3]. Such experiments, utilizing microwave radiation, are practically restricted to frequencies less than 10 GHz. We propose a novel design to generate THz spin waves by laser excitation of an acoustic nanocavity. The idea is to apply a fs-laser pulse to generate a spectrally broad stress pulse in a metallic transducer (TM) layer. Subsequently, the excited acoustic wave packet passes through a ferromagnetic (FM) layer, featuring significant magneto-elastic coupling. Finally, it reaches a superlattice structure, which acts as a frequency selective Bragg mirror for phonons. As a consequence, constructive self-interference leads to the emergence of an acoustic surface mode, with a frequency of several hundreds of GHz, localized in the TM/FM acoustic bilayer cavity. By matching the dispersion of magnons and phonons, energy transfer from the phonon into a magnon mode occurs [4]. As Bragg mirrors, we explore epitaxially grown $LaMnO_3/SrMnO_3$ superlattices, whereas for the functional TM layers we consider β-W or Pt, and for the FM layer $La_{0.7}Sr_{0.3}MnO_3$ or CoFeB. We acknowledge financial support by the DFG within project A02 of the CRC 1073 "Atomic scale control of energy conversion".

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Spin-Charge Conversion and Spin Relaxation Mechanism in Highly-doped π-conjugated Polymer PBTTT

Mohammad M. Qaid*[1], **Olga Zadvorna**[2], **Henning Sirringhaus**[2], **and Georg Schmidt**[1]

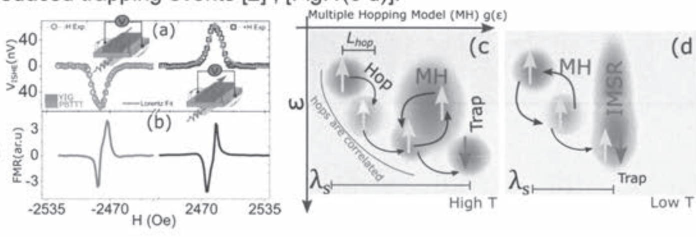
[1] *Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, Von-Danckelmann-Platz 3, 06120 Halle*

[2] *Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom*

***email**: mohammad.qaid@physik.uni-halle.de

Spin pumping can be used to inject a pure spin current from a ferromagnet into a conducting non-magnet. By the inverse spin-Hall effect (ISHE) this spin current can be converted into a charge current, an effect also dubbed spin-charge conversion. Herein, we present the first ever intensive study addressing the detection of spin-to-charge conversion in π-conjugated polymer PBTTT. The polymer is deposited on a ferrimagnetic yttrium iron garnet (YIG) thin film and doped with F4TCNQ [1]. In ferromagnetic resonance a spin current is injected from the YIG into the PBTTT and the ISH-voltage is measured in the organic semiconductor [Fig.1(a-b)]. For our measurements we have used a dedicated geometry which allows to measure very small ISHE signals without artifacts. We investigate the ISHE in PBTTT in different experimental conditions. For each experiment, the polymer thickness, temperature, or doping is varied. The roles of the mobility and charge carrier concentration for the ISHE are also investigated by tuning conductivity which was achieved by varying temperature and doping ratio [1]. We performed an ISHE thickness-dependence study at low temperatures which provided insight into the spin relaxation mechanisms in PBTTT. This study enabled us to extract some of the key parameters of the spin relaxation in highly-doped PBTTT, namely spin diffusion length and spin relaxation time. Our results indicate that the spin relaxation in PBTTT can be explained by EY mechanism. Besides that, the varying of the spin life-time with temperature indicates that the spin is more likely conserved in the hopping events and the spin flip occurs at the thermally reduced trapping events [2] , [Fig.1(c-d)].

Figure 1: (a-b) ISHE and FMR in YIG-PBTTT bilayer . (c-d) The spin relaxation mechanism in PBTTT



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A novel high flux XUV light source for the study of ultrafast element-specific magnetization dynamics

Christina Möller[1], Johannes Otto[1], Henrike Probst[1], Mariana Brede[1], Sabine Steil[1], Daniel Steil[1], Stefan Mathias[1]

[1] 1. Physikalisches Institut, Göttingen, Germany

In recent years, it has been shown that the combination of a femtosecond extreme ultraviolet (XUV) light source with magneto-optical Kerr measurements (MOKE) provides a powerful tool for the study of element-specific magnetization dynamics. Using a high-harmonic based XUV MOKE setup, it was for instance found that femtosecond spin currents drive ultrafast magnetic processes [1,2], how magnetic sublattices interact on femtosecond timescales [3], and that spin dynamics can be induced coherently and directly on the timescale of the optical excitation itself [4,5].

Despite this huge success, however, these first high-harmonic generation (HHG) based MOKE setups were still limited by the available XUV flux, XUV energies, and the sample handling capabilities in terms of temperature control and applied magnetic fields. Here, we present our new element-specific HHG based MOKE experiment, which makes use of a high-repetition rate fiber-based laser amplifier system, and adds high magnetic fields and cooling capabilities to the control of the magnetic sample. We show first element-specific data of a Fe/Ni alloy highlighting the improved signal quality of the setup.

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Ultrafast Lorentz Microscopy: A tool to study laser- and current-driven magnetization dynamics

Möller, Marcel[1], Gaida, John H. [1], Schäfer, Sascha[1], Ropers, Claus[1]

[1]*4th Physical Institute, University of Goettingen, Göttingen, Germany*

Static Lorentz Transmission Electron Microscopy presents itself as a viable method for the mapping of nanoscale magnetic textures, offering a resolution down to one nanometer. In this contribution, we demonstrate its adaptation to time-resolved imaging, offering fascinating prospects for studying ultrafast magnetization dynamics. The Göttingen Ultrafast Transmission Electron Microscope (UTEM) is a newly developed instrument, which allows for studies of ultrafast magnetization and demagnetization dynamics induced by radio-frequency currents or optical pulses. This is facilitated by an electron source which can deliver electron pulses with a duration down to 200 fs.

Here, we focus on the investigation of the gyrotropic motion of a magnetic vortex confined within a 26 nm thick, 2.1µm x 2.1µm permalloy nanoisland [1]. We demonstrate that we can track the vortex core position with an accuracy below 5 nm, measured by the deviation the deviation between identical acquisitions. Furthermore, using a sinusoidal current pulse which only lasts for a cycles, we can trace the build-up and relaxation of the vortex gyration, which reveals a temporal hardening of the free oscillation frequency and an increasing orbital decay rate attributed to local disorder in the vortex potential.

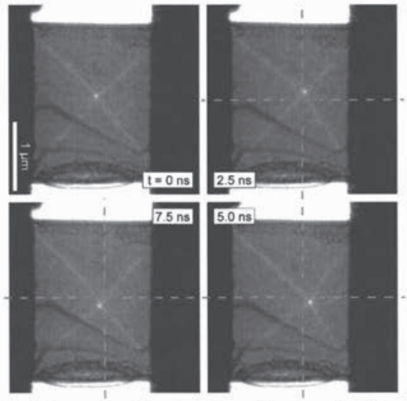

Figure 1. Time-resolved Lorentz micrographs of the gyrotropic motion of the vortex.

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Enhancement of the spin pumping effect by magnon confluence process

Timo B. Noack[1], Vitaliy I. Vasyuchka[1], Dmytro A. Bozhko[1], Björn Heinz[1], Pascal Frey[1], Denys V. Slobodianiuk[2], Oleksandr V. Prokopenko[2], Gennadii A. Melkov[2], Peter Kopietz[3], Burkard Hillebrands[1] and Alexander A. Serga[1]
Email: tnoack@rhrk.uni-kl.de

[1] Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
[2] Faculty of Radiophysics, Electronics and Computer Systems, Taras Shevchenko National University of Kyiv, 01601 Kyiv, Ukraine
[3] Institut für Theoretische Physik, Universität Frankfurt, 60438 Frankfurt, Germany
[4] School of Engineering, University of Glasgow, Glasgow G12 8LT, United Kingdom

The electrical detection of magnon dynamics by means of the spin pumping (SP) and the inverse spin Hall effect (ISHE) is a widely utilized method in the field of magnon spintronics for investigations of magnetization dynamics. Besides its simple realization, one of the main advantages of this approach is the sensitivity to all excited magnons independent from their frequencies and wavevectors. Therefore, the electrical detection of magnons can be efficiently utilized for studies of magnon–magnon scattering processes, when magnons with different wavevectors are involved.

The experimental investigation of the spin pumping process by dipolar-exchange magnons parametrically excited in in-plane magnetized yttrium iron garnet/platinum bilayers is presented [1]. In the field-dependent measurements of the spin pumping-induced component of the ISHE-voltage, a clearly visible sharp peak is detected at high pumping powers. It is found that the peak position is determined by the process of confluence of two parametrically excited magnons into one magnon possessing twice the frequency and the sum of the wavevectors of the initial magnons. Measurements of the peak position at different pumping frequencies clearly show this relation. The three-magnon confluence process constitutes an additional damping mechanism for the group of parametrically pumped magnons. Thus, for low pumping powers the confluence will decrease the total number of magnons in the system. Nevertheless, for high pumping powers the pumping source can compensate this additional damping and the number of magnons is even increasing around the point of confluence.

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Static and time-resolved photoemission electron microscopy of magnetization dynamics triggered by back-side illumination

Maximilian Paleschke, Cheng-Tien Chiang, Wolf Widdra*
Institute of Phyiscs, Martin-Luther-Universität Halle-Wittenberg
Von-Danckelmann-Platz 3, D-06120, Halle (Saale), Germany
*E-mail: wolf.widdra@physik.uni-halle.de

Over the last decades, both ultrafast microscopy and spintronics have progressed in a remarkable manner. Experimental and theoretical methods have been developed in order to understand and eventually control the spin transport and magnetization dynamics approaching the spatial-temporal limit of available techniques [1]. Supported by the newly founded "Collaborative Research Center / Transregio 227 Ultrafast Spin Dynamic" we plan to study spin and magnetization dynamics of magnetic thin films on nanometer-femtosecond scales [2]. Our approach is to combine state-of-the-art time-resolved photoemission electron microscopy (PEEM) with a back-side pumping geometry [3]. With this setup, we would like to image magnetic domains using magnetic dichroism in photoemission [4] and record nm-fs movies of domain switching and domain wall motion triggered by fs spin and optical excitations.

In this poster, we will present the current status of our experimental setup as well as our plans for implementing time resolved measurements. The design of our new vacuum chamber will be shown, which is specified for an optimal optical access in PEEM. Additionally, the corresponding optical beam paths for a flexible combination of back-side pumping with front and back side probing will be discussed. Furthermore, first static images with the different excitation methods of iron surfaces will be presented.

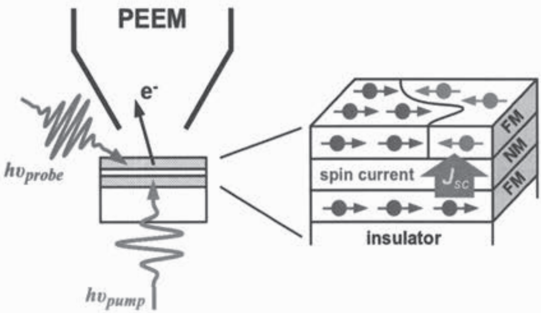

Figure 1: Basic idea of the back-side pump, front-side probe geometry in PEEM. Back-side fs optical excitation on a ferromagnetic (FM) underlying layer triggers a spin current (J_{SC}) that propagates through the non-magnetic (NM) spacer. Because of J_{SC} impinging on the top FM layer, fs domain dynamics occur and can be imaged by time-resolved PEEM at the front side.

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Small-angle x-ray scattering from nanoscale transient magnetic gratings

D. Weder[1], C. von Korff Schmising[1], C. M. Günther[2], M. Schneider[1], B. Pfau[1], B. Vodungbo[3,4], E. Jal[3], X. Liu[3,4], A. Merhe[3,4], F. Capotondi[5], E. Pedersoli[5], J. Lüning[6], and S. Eisebitt[1,2]

[1]Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie im Forschungsverbund Berlin e.V., Berlin, Germany
[2]Technische Universität Berlin, Berlin, Germany
[3]Sorbonne Universités, UPMC Université Paris, Paris, France
[4]CNRS, UMR 7614, LCPMR, Paris, France
[5]Elettra-Sincrotrone Trieste, Basovizza, Trieste, Italy
[6]Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany

Non-local effects like superdiffusive spin and hot-electron transport are considered to be an important channel contributing to optically driven ultrafast magnetization dynamics as well as ultrafast magnetic switching. While the transport along the depth direction of a thin film can be detected with marker layers with sub-nm resolution, lateral transport phenomena in laterally homogeneous films are difficult to resolve. Here we present a time-resolved magnetic small-angle X-ray scattering (SAXS) experiment performed at the free-electron laser facility FERMI to study and quantify ultrafast superdiffusive spin and/or hot-electron transport dynamics in reciprocal space. We investigated magnetic Co/Pd multilayers with perpendicular magnetic anisotropy capped by thin aluminium gratings with periodicities between 220 nm and 256 nm. The Al gratings structure and localize the ultrafast optical excitation leading to the formation of transient gratings of magnetized and demagnetized areas in the multilayer. Based on the detection of resonant scattering (Co M-edge at 20.8 nm) from the gratings up to the fifth order, we are able to laterally resolve the transient spin configuration with interferometric resolution (< 4 nm). Within this limit, we do not find evidence for transport processes significantly contributing to the demagnetization.

Direct imaging of the localized spin dynamics in confined micro structures using time-resolved STXM

S. Pile[1], T. Feggeler[2], T. Schaffers[1], R. Meckenstock[2], M. Buchner[1], D. Spoddig[2], V. Ney[1], H. Wende[2], R. Narkowicz[3], K. Lenz[3], J. Lindner[3], H. Ohldag[4], K. Ollefs[2], and A. Ney[1]

[1]Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, 4040 Linz, Austria
[2]Faculty of Physics and Center for Nanointegration Duisburg-Essen (CENIDE), University of Duisburg-Essen, 47057 Duisburg, Germany
[3]Helmholtz-Zentrum Dresden-Rossendorf, Germany
[4]Stanford Synchrotron Radiation Laboratory, SLAC National Accelerator Laboratory, Menlo Park, CA

For the development of novel spintronic devices it is important to understand the dynamic magnetic processes on the micro- and nanoscale [1]. By using lithographically fabricated micro resonators it is possible to measure FMR of the small samples with a detection sensitivity of down to 10^6 spins [2]. Possibilities of these micro resonators allow combining STXM with XMCD spectroscopy and FMR (STXM-FMR). This STXM-FMR setup enables the visualization of the high frequency magnetization dynamics in the GHz regime with a high lateral resolution of nominally 35 nm and a time resolution of 17.4 ps [3]. In this contribution we present the results for the magnetic $Ni_{80}Fe_{20}$ micron-sized stripes with dimensions: 5x1x0.03 μm^3.
For STXM-FMR measurements a static magnetic field was applied in the plane of the stripes parallel to the long axis of one stripe ("easy orientation") and perpendicular to the long axis of another ("hard orientation"). The influence of the circular polarization on the dynamic magnetic contrast at ferromagnetic resonance was investigated by switching the polarization between measurements. The STXM-FMR measurements complement previous FMR measurements. Quasi-uniform and spin-wave modes were visualized using STXM-FMR. The results show, that with increasing the static magnetic field it is possible to observe the transition from one mode to another and additionally observe superposition of the modes in between the FMR signals.
Financial support by the Austrian Science Fund (FWF), Project No. I-3050, ORD-49 and the German Research Foundation (DFG), Project No. 321560838 is gratefully acknowledged.

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Study of Ultrafast Magnetization Dynamics in Perovskite Oxide thin Films by use of Extreme Ultraviolet Light

Henrike Probst[1], Johannes Otto[1], Christina Möller[1], Cinja Seick[1], Sabine Steil[1], Daniel Steil[1], Vasily Moshnyaga[1] and Stefan Mathias[1]

[1]1. Physikalisches Institut, Göttingen, Germany

Ultrafast spin dynamics has become an active field of research since the seminal work of Beaurepaire in 1996 [1]. Thereafter, numerous experimental and theoretical works have been conducted to understand the microscopic mechanisms governing the light-matter interaction of magnetic materials on a femtosecond timescale.

However, ultrafast magnetization dynamics in complex systems such as alloys, multilayers and strongly correlated electron systems are not much explored. In particular, in strongly correlated electron systems, electrons, spins and lattice are interconnected. Therefore, these materials show a collective response to a photo-excitation, and the different contributions of electrons, spin and lattice to the dynamics are hard to disentangle with usual time-resolved methods [2].

In our project, we make use of the resonant magneto-optical Kerr effect in the extreme-ultraviolet (XUV) regime. Being resonant to the M-absorption edges of Ni, Fe, Mn, and Co provides an increased sensitivity to the pure magnetic signals and furthermore an element-specific probe.
We will present first element-specific data on high qualitative thin perovskite films prepared by metalorganic aerosol deposition technique.

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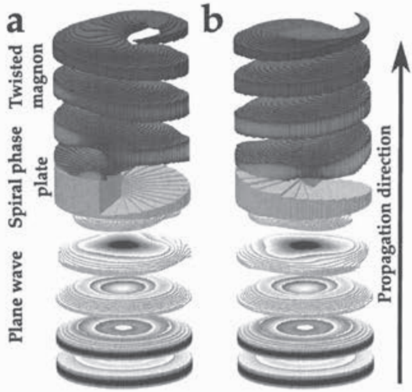
Twisting and tweezing the spin wave: on vortices, skyrmions, helical waves, and the magnonic spiral phase plate

C. Jia[1], D. Ma[1], A. F. Schäffer[2], and J. Berakdar[2]

[1]*Key Laboratory for Magnetism and Magnetic Materials of the Ministry of Education & Institute of Theoretical Physics, Lanzhou University, China*
[2] *Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, Karl-Freiherr-von-Fritsch-Str. 3, 06120 Halle (Saale), Germany*

Spin waves are the low-energy excitations of magnetically ordered materials. They are key elements in the stability analysis of the ordered phase and have a wealth of technological applications. Recently[1], we showed that spin waves of a magnetic nanowire may carry a definite amount of orbital angular momentum components along the propagation direction. This helical, in addition to the chiral, character of the spin waves is related to the spatial modulations of the spin wave phase across the wire. It, however, remains a challenge to generate and control such modes with conventional magnetic fields. Therefore, we propose the magnetic spiral phase plate by appropriately synthesizing two magnetic materials that have different speeds of spin waves in a subsequent project[2].



In this contribution, we discuss the key features of helical spin waves and demonstrate the functionality of the magnonic spiral phase plate with micromagnetic simulations. Despite the complicated structure of demagnetization fields, a homogeneous spin wave passing through the spiral phase plate attains the required twist and propagates further with the desired orbital angular momentum. While excitations from the ordered phase may have a twist, the magnetization itself can be twisted due to internal fields and forms, which is known as a magnetic vortex. We point out the differences between both types of magnetic phenomena and discuss their possible interactions.

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Imaging and writing magnetic domains in the non-collinear antiferromagnet Mn_3Sn

H. Reichlova[1], T. Janda[2], J. Godinho[3,2], A. Markou[4], Dominik Kriegner[4,3], R. Schlitz[1], J. Zelezny[3], Z. Soban[3], M. Bejarano[5], H. Schultheiss[5], P. Nemec[2], T. Jungwirth[3], C. Felser[4], J. Wunderlich[3], S. T. B. Goennenwein[2]

[1]Institut für Festkörper- und Materialphysik and Würzburg-Dresden Cluster of Excellence ct.qmat, Technische Univeristät Dresden, Dresden, Germany
[2] Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
[3] Institute of Physics ASCR, v.v.i., Praha, Czech Republic
[4] Max Planck Institute for Chemical Physics of Solids, Dresden, Germany
[5] Helmholtz-Zentrum Dresden-Rossendorf,Institute of Ion Beam Physics and Materials Research, Dresden, Germany

Non-collinear antiferromagnets (AFM) feature vanishing magnetic stray fields while maintaining a large magnetotransport response. Harnessing these unique properties will be essential for exploiting the full potential of antiferromagnetic spintronics. As part of this development, techniques for imaging and writing of the microscopic spin arrangement, namely the magnetic domain distribution and the domain orientations in non-collinear AFMs must be developed.
Here, we demonstrate that the local magnetic structure in thin films of the non-collinear AFM Mn3Sn can be imaged by scanning thermal gradient microscopy (STGM). The technique is based on scanning a laser spot over the sample's surface and recording the ensuing thermo-voltage. We image the magnetic structure at a series of different temperatures and show that at room temperature, the domain structure is not affected by the application of moderate magnetic fields. In addition to imaging, we establish a scheme for heat-assisted magnetic recording, using local laser heating in combination with magnetic fields to intentionally write domain patterns into the antiferromagnet.

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Current induced switching of epitaxial NiO(111)/Pt and CoO(001)/Pt bilayers

L. Baldrati[1], O. Gomonay[1], A. Ross[1,2], M. Filianina[1,2], R. Lebrun[1], R. Ramos[3], C. Leveille[1], C. Schmitt[1], T. R. Forrest[4], F. Maccherozzi[4], E. Saitoh[3,5,6,7,8], J. Sinova[1], M. Kläui[1,2]

[1]Institute of Physics, Johannes Gutenberg-University Mainz, 55128 Mainz, Germany
[2]Graduate School of Excellence Materials Science in Mainz, 55128 Mainz, Germany
[3]Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
[4]Diamond Light Source, Chilton, Didcot, Oxfordshire OX11 0DE, United Kingdom
[5]Institute for Materials research, Tohoku University, Sendai 980-8577, Japan
[6]Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan
[7]Center for Spintronics Research Network, Tohoku University, Sendai 980-8577, Japan
[8]Department of Applied Physics, The University of Tokyo, Tokyo 113-8656, Japan

mailto: schris04@students.uni-mainz.de

We probe current-induced switching in Hall crosses patterned on epitaxial NiO(111)/Pt bilayers and on CoO(001)/Pt bilayers, insulating antiferromagnet/heavy metal thin film systems[1,2]. Spin Hall magnetoresistance (SMR) measurements allow to read the orientation of the Néel vector. In particular, the transverse voltage (measured in a Hall-like geometry) is proportional to the product of the Néel vector components n_x*n_y [3]. The data acquisition is performed by applying current pulses of different current density to the sample and by measuring the transverse voltage after relaxation of the state. We find that switching effects not related to the magnetic properties exist, as we observe by probing MgO/Pt reference samples [4]. By looking at the switching above and below the Neél temperature in CoO/Pt we can clarify the interplay between magnetic and non-magnetic effects. The effect related to the magnetic properties of the samples disappears above Néel temperature whereas the non-magnetic effect can be attributed to a local annealing process in the Platinum layer and does not disappear above Néel temperature. Further we find that a NiO(111) 90 nm thick sample switches more easily than a 5 nm sample whereas in CoO the thickness dependence is different [4].

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Domain wall dynamics of ferrimagnets in thermal magnon currents

A. Donges[1], N. Grimm[1], F. Jakobs[1,2], S. Selzer[1], U. Ritzmann[1,2], U. Atxitia[1,2] and U. Nowak[1]

[1]Universität Konstanz, Universitätsstraße 10, DE-78457 Konstanz, Germany
[2]Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, Arnimallee 14, DE-78457 Berlin, Germany

Control of magnetic domain wall dynamics is key for efficient manipulation of magnetically stored information. Thermal magnon currents, generated by temperature gradients, can be used to move magnetic textures. For ferromagnetic and antiferromagnetic domain walls, this motion was investigated theoretically with the finding that domain walls always move towards the hotter end of the thermal gradient [1,2,3]. By numerical studies and complementary analytical calculations, we demonstrate that domain walls in ferrimagnets show much richer dynamics allowing movement in both directions [4]. This due to the competition of angular momentum transfer and entropic torque.

Below the Walker breakdown, the temperature gradient always pulls the wall towards the hot end due to an entropic torque, which ensues from the minimization of free energy, in agreement with previous theoretical studies for ferro- and antiferromagnets [1,2,3]. Above the Walker breakdown, however, the ferrimagnetic domain wall is driven by angular momentum transfer, which can move the wall in both directions, a feature unique to ferrimagnets since it is related to the angular momentum compensation temperature. In particular, we find that below the compensation temperature the wall moves towards the cold end, whereas above it, towards the hot end. Moreover, for ferrimagnets, there is a torque compensation temperature at which the domain wall dynamics shows similar characteristics to antiferromagnets, that is, quasi-inertia-free motion and the absence of the Walker breakdown.

This finding opens the door for fast control of ferrimagnetic domains on account of the antiferromagnetic character while conserving the advantage of ferromagnets in terms of measuring and control by conventional means such as magnetic fields.

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Paramagnetic molecuels on Magnetite as a spin-current detector

T. Strusch[1], R. Meckenstock[1], Y. Nalench[2], M. Abakumov[2], M. Farle[1], U. Wiedwald[1]

[1]*Faculty of Physics and CENIDE, University of Duisburg-Essen, 47048 Duisburg, Germany*

[2]*National University of Science and Technology NUST MISIS, Moskow, Russian Federation*

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 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 Magnetite (Fe_3O_4) nanoparticles (NPs) with a diameter of 15 nm 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 carbon chain [4]. The ferromagnetic resonance (FMR) of the Fe_3O_4 NPs generates 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 results 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 linearly increases with the square root of the microwave power [1]. Here, we show that the second EPR signal S2 at the OA double bond with a linewidth of $\Delta B_{pp} < 0.1$ mT decreases exponentially with increasing microwave power. We explain this by the dipole interaction of S1 and S2 and their different lifetimes.

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Towards Room Temperature Ferromagnetism in magnetic ZnO with stable Bound Magnetic Polarons

Sahitya V. Vegesna,[1,2] T. Kaspar,[3] D. Bürger,[4] J. Grebing,[3] I. Skorupa,[3,4] J. Grenzer,[3] R. Hübner,[3] S.Q. Zhou,[3] Oliver G. Schmidt,[4,5] and Heidemarie Schmidt[1,2,4*]

[1]Leibniz-Institut für Photonische Technologien, 07745 Jena, Germany
[2]Institut für Festkörperphysik mit dem Schwerpunkt Quantendetektion, Friedrich-Schiller-Universität Jena, 07743 Jena, Germany
[3]Institute of Ion-Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf e.V. (HZDR), Dresden, 01328, Germany
[4]Material Systems for Nanoelectronics, Chemnitz University of Technology, Chemnitz 09126, Germany
[5]Institute for Integrative Nanosciences, IFW Dresden, Dresden 01069, Germany

Stable bound magnetic polarons (*BMP*) are formed in depleted regions of *ZnCoO* with isovalent cobalt ions surrounding an oxygen vacancy in the BMP center. For a given concentration of isovalent *Co* ions, we consider the BMP increased dielectric constant in *ZnCoO* to determine the minimum concentration of oxygen vacancies in order to realize percolating *BMPs*. Clear fingerprints of stable *BMPs* are detected in magnetization and magnetotransport [1] data of depleted *ZnCoO* thin films. A sophisticated control on the concentration of intrinsic defects and of magnetic ions during deposition along with precise determination of the corresponding dielectric constant are the main ingredients that guide researchers towards ferromagnetism in transparent spintronics. We also revealed that *BMP* can be stabilized if the magnetic transition metal oxides are depleted from free carriers. The clear fingerprint of BMP formation is an additional step in magnetic susceptibility where the large collective spins of isovalent *Co* ions align. Furthermore, a huge decrease of mobility of hopping charge carriers is observed. This is related with increased spin scattering effects between spin polarised charge carriers hopping between the oxygen vacancies in the *BMP* centre and the electron spin of those oxygen vacancies. Our work shows that magnetization and magnetotransport [2] properties of magnetic *ZnO* with stable *BMPs* can be controlled by both electric and magnetic field [3].

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Optical intersite spin transfer probed by helicity dependent transient absorption spectroscopy

Clemens von Korff Schmising[1], Felix Willems[1], Christian Strüber[1], Daniel Schick[1], Dieter W. Engel[1], J. K. Dewhurst[2], Peter Elliot[1], Sangeeta Sharma[1] and Stefan Eisebitt[1,3]

[1] Max Born Institute, Max-Born-Str. 2A, 12489 Berlin, Germany

[2] Max-Planck-Institute for Microstructure Physics, Weinberg 2, 06120 Halle (Saale), Germany

[3] Institut für Optik und Atomare Physik, Technische Universität Berlin, 10623 Berlin, Germany

Optically driven spin transport is the fastest and most efficient process to manipulate macroscopic magnetization, as it does not rely on secondary mechanisms to dissipate angular momentum [1]. In our conference contribution, we show in a joint theoretical and experimental work, that calculated and measured changes of the helicity dependent absorption at the resonant $M_{2,3}$ transition of Co in the extreme ultraviolet spectral range gives clear evidence that optical induced spin transfer (OISTR) from Pt to Co governs the ultrafast magnetization dynamics of a CoPt alloy [2]. The origin for this laser-driven spin current are available minority states above the Fermi level, making this a general phenomenon in all multi-component magnetic systems.

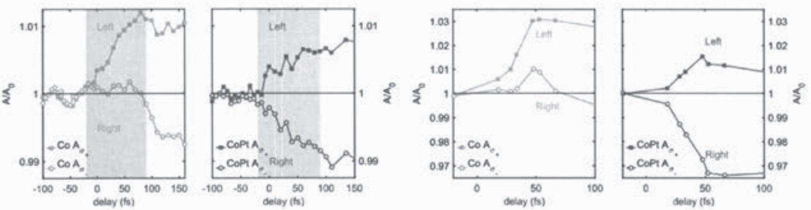

Fig. 1. Measured (left panel) and calculated (right panel) helicity dependent absorption, A/A_0, of Co and CoPt at the Co resonance at 60.3 eV. Supported by theoretical calculations, we attribute absorption with right/left circular polarization, $A_{\sigma\pm}$, predominantly to transitions to minority/majority valence states. At the Co resonance at 60.3 eV, the increase of is due to laser-excitation of electrons above the Fermi energy resulting in additional available states for absorption. More surprising are the distinct difference observed in the minority channel between the CoPt alloy and the Co film. We explain the observed very rapid decrease of $A_{\sigma-}$ (right) absorption in CoPt by an efficient filling of empty Co minority states, mediated by optical spin transfer (OISTR) from Pt electrons.

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Efficiency of ultrafast optically-induced spin transfer in Heusler compounds

D. Steil[1], J. Walowski[2], F. Gerhard[3], T. Kiessling[3], D. Ebke[4], A. Thomas[5], T. Kubota[6], M. Oogane[7], Y. Ando[7], J. Otto[1], A. Mann[1], M. Hofherr[8], P. Elliott[9], J. K. Dewhurst[10], G. Reiss[4], L. Molenkamp[3], M. Aeschlimann[8], M. Cinchetti[11], M. Münzenberg[2], S. Sharma[9] and S. Mathias[1]

[1]I. Physikalisches Institut, Universität Göttingen, Germany
[2]Institut für Physik, Universität Greifswald, Germany
[3]Physikalisches Institut (EP3), Universität Würzburg, Germany
[4]Department of Physics, Bielefeld University, Germany
[5]Leibniz Institute IFW Dresden, Germany
[6]IMR and CSRN,Tohoku University, Sendai, Japan
[7]Department of Applied Physics and CSRN, Tohoku University, Sendai, Japan
OPTIMAS, University of Kaiserslautern, Germany
[9]Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie, Berlin, Germany
[10]Max-Planck-Institut für Mikrostrukturphysik, Halle, Germany
[11]Experimentelle Physik VI, TU Dortmund, Germany
E-mali: jakob.walowski@uni-greifswald.de

Ultrafast magnetization dynamics, creates knowledge for practical applications by exploring the speed of switching for magnetic storage as well as for the scientific challenge of understanding strongly-coupled systems. Recent breakthroughs are the experimental verification of the optically-induced spin transfer (OISTR) effect [1], which enables optical control of the magnetization in a material down to attosecond timescales [2]. Showing, that the direct interaction of the laser field with the material creates transient non-equilibrium states, which can exhibit an efficient spin-transfer between different magnetic subsystems. Leaving unclear, whether OISTR is a general phenomenon for efficient spin dynamics manipulation in magnetic materials.
We present a comprehensive study of the novel OISTR effect in Heusler compounds. Half Heuslers (NiMnSb, CoMnSb) show strong OISTR signatures, while in full Heuslers (Co_2MnSi, Co_2FeSi, Co_2FeAl) this signature is weaker, agreeing with ab-initio calculations. The results elucidate the physical mechanisms responsible for the OISTR process efficiency, give optimization guidance for direct optical magnetization control in complex materials, and provide quantified experimental evidence of OISTR as a general phenomenon.

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Exchange-Enhanced Ultrastrong Magnon-Magnon Coupling in a Compensated Ferrimagnet

L. Liensberger[1,2], A. Kamra[3], H. Maier-Flaig[1,2], S. Geprägs[1], A. Erb[1], S. T. B. Goennenwein[4], R. Gross[1,2,5,6], W. Belzig[7], H. Huebl[1,2,5,6], and M. Weiler[1,2]

[1]*Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany*
[2]*Physik-Department, Technische Universität München, 85748 Garching, Germany*
[3]*Center for Quantum Spintronics, Department of Physics, Norwegian University of Science and Technology, 7491 Trondheim, Norway*
[4]*Institut für Festkörper- und Materialphysik, Technische Universität Dresden, 01062 Dresden, Germany*
[5]*Nanosystems Initiative Munich, 80799 Munich, Germany*
[6]*Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany*
[7]*Department of Physics, University of Konstanz, 78457 Konstanz, Germany*

The strong and ultrastrong interaction of light and matter is foundational for circuit quantum electrodynamics. The coupling of quasiparticles (magnons) and electromagnetic waves allows for coherent control and engineering of spin dynamics for applications in optomagnonics, such as frequency up-conversion. Antiferromagnets and ferrimagnets moreover host multiple magnon modes. The mutual coupling of these modes has great appeal for applications in antiferromagnetic spintronics.

Here, we experimentally study the spin dynamics in a gadolinium iron garnet single crystal using broadband ferromagnetic resonance [1]. Close to the ferrimagnetic compensation temperature, we observe ultrastrong coupling of clockwise and counterclockwise magnon modes. The magnon-magnon coupling strength reaches almost 40% of the mode frequency and can be tuned by varying the direction of the external magnetic field. We theoretically explain the observed mode coupling as arising from the broken rotational symmetry due to a weak magnetocrystalline anisotropy. The effect of this anisotropy is exchange enhanced around the ferrimagnetic compensation point.

The ultrastrong and size-independent magnon-magnon coupling reported here opens exciting perspectives for studying ultrastrong coupling effects in nanoscale devices and exploring quantum-mechanical coupling phenomena beyond classical electrodynamics.

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Spin-orbitronics based on a vdW antiferromagnetic semiconductor

Rui Wu[1,2], Romain Lebrun[1], Shilei Ding[1], Franziska Martin[1] & Mathias Kläui[1,2]

[1]*Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudinger Weg 7, 55128 Mainz, Germany*

[2]*Centre for Quantum Spintronics, NTNU, 7491 Trondheim, Norway*

The coupling between spin and orbit in materials has led to a new direction in spintronics, i.e. spin-orbitronics in oxides[1]. This approach relies on spin-orbit coupling (SOC) effects instead of the exchange interaction effects to generate, detect or exploit spin-polarized currents. Due to the ultrafast (~THz) dynamics and high stability with respect to external fields antiferromagnetic materials including metals, semiconductors and insulators are excellent candidates for future spintronics devices[2]. We will summarize our experimental results of spin-orbitronics in vdW AFM semiconductors and show that effects are observed that result from the low-dimensionality of the studied systems that make them distinct from bulk systems. We have focused on the spin-Hall magnetoresistance (SMR)[3] in such systems, which provide insights into the strong interaction between the surface spin polarization in the 2d materials and the nonequilibrium spin accumulation of the Pt electrode resulting from the spin-Hall effect. We find an anomalous Hall effect at temperatures above the Néel temperature of the bulk materials, which might originate from the proximity effect at the interface between the vdW magnet and heavy metal.

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