Re-thinking Spintronics: From Unconventional Materials to Novel Technologies

776. WE-Heraeus-Seminar

04 – 06 January 2023

hybrid

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 776. WE-Heraeus-Seminar:

Spintronics is at the heart of modern research in the field of magnetism aiming towards the design of low-power, ultra-fast, robust and high-density storage and information processing devices. This has sparked an intensive search for new experimental and theoretical approaches to understand and manipulate existing systems and to design and develop new ones. Of particular interest is the possibility to utilize features of electronic bands and broken symmetry on an atomistic and micromagnetic scale. Materials with complex magnetic ordering pave the path towards novel, technologically promising static and dynamic properties in magnetic topological solitons and magnonic systems. Furthermore, recently developed techniques such as electron beam deposition or nitrogen-vacancy centre magnetometry offer new avenues in geometry-driven applications and accessing subtle details of ordering at the nanoscale.

This seminar aims to provide a platform for developing and formulating future pathways in the field of spintronics. The focus will be on four of the most promising and innovative areas of spintronics: design and engineering of novel material systems with a separate spotlight on antiferromagnets, charge-free data transfer and processing techniques relying on spin waves, and development of new tools in fabrication, characterization, detection, and analysis of planar and 3D architectures on the nanoscale. Leading experts will present the state-of-the-art, recent findings and open challenges in spintronics and kick-off a stimulated discussion on promising avenues in the field. Participants of the Seminar are invited to present their research at poster sessions.

Scientific Organizers:

Prof. Dr. Angela Wittmann	Universität Mainz, Germany E-mail: a.wittmann@uni-mainz.de
Dr. Oleksandr V. Pylypovskyi	Helmholtz-Zentrum Dresden-Rossendorf, Germany E-mail: o.pylypovskyi@hzdr.de

Introduction

Administrative Organization:

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Tuesday (17:00 h – 21:00 h) and Wednesday morning

Program

Program

Tuesday, 03 January 2023

17:00 – 20:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Wednesday, 04 January 2023

08:00	*BREAKFAST*	
09:00	Scientific organizers	**Welcome words**
09:15 – 10:00	Nicola Spaldin	**Concepts from multiferroics that might be useful for spintronics**
10:00 – 10:45	Caroline Ross	**Magnetic garnets for spintronics**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 12:00	Katsuya Inoue	**Chiral material sciences**
12:00 – 12:45	Yossi Paltiel	**Efficient spintronics utilizing the chiral induced spin selectivity(CISS) effect**
12:45 – 13:00	David Janas	**Enhancing electron correlation at a 3d ferromagnetic surface: a pathway to access novel material properties?**
13:00	*LUNCH*	

Program

Wednesday, 04 January 2023

14:30 – 15:30	**Poster session**	
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Philipp Pirro	**Nonlinear magnonics for unconventional computing**
16:45 – 17:30	Angelo Di Bernardo	**Superconducting spintronics: open challenges and new materials platforms**
17:30 – 17:45	Jonathan Kipp	**Interaction parameters in magnetic 2D systems from symmetric invariants**
17:45 – 18:00	William Legrand	**Nanomagnets for electric dipole spin resonance and spin–photon coupling**
18:00	*DINNER*	
19:30	Petra Rudolf	**Evening talk:** **Unconscious bias: how it impacts careers in science and how to mitigate this influence**

Program

Thursday, 05 January 2023

08:00	*BREAKFAST*	
09:00 – 09:45	Libor Šmejkal	**Altermagnetism: spin symmetry foundations and unconventional spintronics effects**
09:45 – 10:30	Helena Reichlova	**Magneto-thermal transport in compensated magnets**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Olena Gomonay	**Gradient magnetoelasticity: Tailoring and manipulation of antiferromagnetic textures**
11:45 – 12:30	Stavros Komineas	**Dynamics of solitons in antiferromagnets**
12:30 – 12:45	Sumit Ghosh	**Manipulating topology of massive Dirac Fermion with scalar potential**
12:45 – 12:55	**Conference Photo** (in the front of the lecture hall)	
12:55	*LUNCH*	

Program

Thursday, 05 January 2023

14:30 – 15:15	Lucas Caretta	**Manipulating excitations in magnetic complex oxides**
15:15 – 16:00	Jörg Wunderlich	**Non-volatile spin-orbit torque driven antiferromagnetic memristor**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Christian Degen	**Quantum imaging of antiferromagnetic and ferroelectric textures**
17:15 – 18:00	Alina Deac	**Tunable Vortex dynamics in ion-implanted disks**
18:00 – 18:15	Lisa-Marie Kern	**Imaging nanometer-scale skyrmion (de)formation dynamics**
18:15 – 18:30	Alla Bezvershenko	**Walking skyrmions**
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	
20:00	*Posters* *Informal get-together (open end)*	

Program

Friday, 06 January 2023

08:00	*BREAKFAST*	
09:00 – 09:45	Michael Huth	**Direct-write nanofabrication with focused electron beams for 3D nano-magnetism**
09:45 – 10:30	Claas Abert	**Recent advances in micromagnetic simulation**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Claudia Felser	**Topology for energy efficient spintronics and energy conversion**
11:45 – 12:00	Scientific organizers	**Awards & closing remarks**
12:00	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Saturday; however, a self-service breakfast will be provided on Saturday morning

Posters

Posters

Hassan Al-Hamdo	**Magnetization dynamics in hybrid ferromagnetic/antiferromagnetic systems**
Matthias Althammer	**Observation of nonreciprocal magnon Hanle effect**
Olha Bezsmertna	**Transfer printing of GMR sensing elements for curved electronics**
Yelyzaveta Borysenko	**Magnetic field-induced textures and phase transitions in antiferromagnetic spin chains: geometry-induced effects**
Grzegorz Centała	**Flat bands in magnonic Lieb lattices**
Silvia Damerio	**Magnetic properties of sputtered terbium iron garnet thin films**
Claire Donnelly	**Complex free-space magnetic field textures induced by three-dimensional magnetic nanostructures**
Hans-Joachim Elmers	**Critical behavior and exchange splitting in the antiferromagnet monolayer Mn on Re(0001)**
Jose A Fernandez Roldan	**Curvilinear phenomena in magnetization dynamics and in stray field**
William Griggs	**Skyrmionics for neuromorphic computing**
Sebastian Guerrero Soriano	**Cryogenic NV magnetometry applied to multiferroics**
Rahul Gupta	**Direct evidence of superdiffusive terahertz spin current arising from ultrafast demagnetization process**
Christopher Heins	**Spontaneous emergence of spin-wave frequency combs mediated by vortex gyration**

Posters

Hauke Lars Heyen	**Current driven skyrmion movement and their electrical detection in Ta/CoFeB/MgO**
Rhea Hoyer	**Topological hybrids of magnons and magnon bound pairs**
Chanyong Hwang	**Magnetic skyrmion season II**
Marcel Kohlmann	**Tuning all-optical magnetization switching efficiency by laser pulse wavelength variation**
Paul Lehmann	**Surface magnetization of Cr¬2O3 (104) quantified via scanning NV magnetometry**
Kai Litzius	**Stability and nucleation of magnetic skyrmions in the 2D van der Waals magnets Fe3GeTe2**
Pavlo Makushko	**Flexomagnetism and vertically graded Néel temperature of antiferromagnetic Cr2O3 thin films**
Nicholas Meinhardt	**Time-resolved scanning NV magnetometry of dynamic domain walls**
Sebastian Meyer	**Spin-current driven Dzyaloshinskii-Moriya interaction in the multiferroic BiFeO3 from firstprinciples**
Ashish Moharana	**Chiral induced spin selectivity effect at molecules metal hybrid interfaces**
Jonah Elias Nitschke	**Angle-resolved photoemission study of transition metal phosphorus trisulfides in the 2D limit**
Johannes Paul	**Recent trends in magnetic sensor demands**
Daniele Preziosi	**Spinel FeV2O4: A new opportunity in spintronics**

Posters

Sonny H. Rhim	**Berryology and anomalous hall effect in compensated ferrimagnet**
Mohammad Reza Safari	**Enantiospecific adsorption on a ferromagnetic surface at the single-molecule scale**
Daniel Schroller	**Readout of single molecule magnets with semiconductor spin qubits**
Helmut Schultheiss	**Approaching machine learning with nonlinear magnonic hardware**
Shahrukh Shakeel	**Experimental investigation of mesoscale Dzyaloshinskii-Moriya interaction**
Julian Skolaut	**Imaging the antiferromagnetic domain structure of hematite and its magnetic field dependence**
Krzysztof Sobucki	**Magnon-optic effects with spin-wave leaky modes in Gires-Tournois interferometer**
Boris Sorokin	**Development of ultrafast soft X-ray magnetic holography at SwissFEL**
Abolfazl Tavakoli	**Optically induced spin dynamics in exchange-coupled spin models**
Andy Thomas	**In-situ correlation of electrical (magneto-)transport effects with magnetic textures in a transmission electron microscope**
Vitaliy Vasyuchka	**ElElectric control of magnon phase and magnonic Aharonov-Casher effect**
Ihor Veremchuk	**Defect nanostructure and its impact on magnetism of α-Cr_2O_3 thin films**

Posters

Lucas Vollroth	**Kerr microscopy for all-optical helicity-dependent magnetization switching (AOHDS)**
Clemens von Korff Schmising	**Ultrafast response of induced and intrinsic magnetic moments in 3d/5d material systems**
Tobias Wagner	**Exchange enhancement of ferromagnetic resonance frequencies in Mn2Au/Ni80Fe20**

Abstracts of Talks

(in alphabetical order)

Recent advances in micromagnetic simulation

C. Abert[1]

[1]*University of Vienna, Faculty of Physics, Vienna, Austria*

Computational micromagnetics has become an indispensable tool for the theoretical investigation of magnetic structures. Classical micromagnetics has been successfully applied to a wide range of applications including magnetic storage media, magnetic sensors, magnonic systems, permanent magnets and more. In recent years, a lot of research in the micromagnetics community has been conducted on the performance increase of simulation tools. Novel highly parallel hardware has shown to be a game changer for the simulation of large systems. On the other hand, the recent advent of spintronics devices has led to various extensions to the micromagnetic model in order to account for spin-transport effects [1]. Besides the use of micromagnetic software for the simulation of given systems, high performance hardware and novel algorithms have paved the way for the new discipline of inverse micromagnetics, where highly dimensional system parameters such as the geometry are optimized with respect to time dependent objectives in order to design novel devices. This talk is aimed to give an overview over recent developments in models, algorithms and simulation tools for the investigation of magnetic systems.

References

[1] C. Abert, The European Physical Journal B **92.6**, 1-45 (2019)

Walking Skyrmions

Alla Bezvershenko[1] **and Achim Rosch**[1]

[1] *Institute for Theoretical Physics, University of Cologne, Cologne, Germany*

We study the pinning - unpinning transition of the skyrmion lattice in bulk MnSi under applying a slowly oscillating transverse magnetic field. We model the system using an elastic model for skyrmion strings in the presence of pinning forces. With this effective model we show that the presence of a transverse magnetic field reduces the critical current density needed to depin the skyrmion lattice, reaching zero at the critical magnetic field value. Further, the complete phase diagram of this model will be discussed. Below the threshold amplitude, the skyrmion lines stay fully pinned. Upon increasing the amplitude, a so-called "walking" phase starts, where the skyrmion lines start to unpin. If in this phase a sufficiently large electric current is being applied, the skyrmion lattice starts to move. Obtained results are compared to the experimental data on the transverse susceptibility measurements for this system.

Manipulating Excitations in Magnetic Complex Oxides

L. Caretta[1], S.K. Kim[2], J. Analytis[3], K.J. Lee[2], C. Ross[4], G Beach[4], R. Ramesh[3]

[1]Brown University, Providence, Rhode Island, USA
[2] Korea Advanced Institute of Science and Technology, Daejeon, Korea
[3]University of California, Berkeley, California, USA
[4]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Excitations in magnetic materials, such as domain walls, skyrmions, cycloids, and spin waves provide a rich playground for studying intriguing physical phenomena like chirality, topology, and spin-orbit interactions. Additionally, these excitations hold vast technological potential. For example, domain walls and skyrmions, which can be nucleated, annihilated, and translated by electrical stimuli, provide a promising approach to encode bits of information for next-generation memory and logic. Additionally, magnons, which can be generated by electrical or thermal mechanisms, can carry information with low Ohmic losses. One technological and scientific challenge is to stabilize and manipulate these magnetic excitations efficiently. This is critical for dense, power efficient, and fast beyond-CMOS memory and logic. However, in traditional metallic ferromagnetic materials, these excitations face latency, energy consumption, and bit size challenges preventing their use in any competitive technologies. On the other hand, complex oxides exhibit a rich spectrum of functional responses, including multiferroicity, highly correlated electron behavior, and more. By synthesizing and engineering new classes of spintronic oxide materials systems, we show a pathway to overcome these fundamental limitations. Specifically, by using a combination of epitaxial growth techniques, interface design, and magnetic sublattice engineering, we drive magnetic domain walls to velocities over 4,300 m/s [1,2]. Furthermore, I will show progress towards low-power and scalable electric-field control of magnons and provide pathways for energy efficient spin-to-charge interconversion [3]. Finally, by using advanced electrical and optical techniques (and developing new ones), we show that these systems provide a new platform to study complex fundamental phenomena like inversion symmetry-breaking and even relativistic dynamics.

References

[1] Caretta, L. *et al. Science* 1442, 1438–1442 (2020)
[2] Caretta, L. *et al. Nat. Commun.* 11, 1090 (2019)
[3] Parsonnet, E. *et al. Phys. Rev. Lett.* 129, 087601 (2022)

Tunable Vortex Dynamics in Ion-Implanted Disks

A.M. Deac[1]

[1]*Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany*

The magnetic “vortex” is a potential candidate for future spintronic devices, such as low-noise magnetic sensors[1], frequency sensors[2], and tunable magnonic crystals[3]. More recently, coupled vortex spin-torque oscillators have been integrated into complex circuits which can be “trained” to recognize a series of sounds[4] by exploiting their ability to synchronize on external ac field or current signals, offering an exciting new path for neuro-inspired computing[5].

Vortex-based spin-torque oscillators offer narrow linewidth and are relatively unaffected by thermal noise when compared to their single-domain counterparts. However, the frequency tunability of vortex-based devices is limited, since the gyrotropic frequency is specific to the individual sample design. To overcome this drawback, in this work[6], we induced regions of different saturation magnetizations in single magnetic disks by ion implantation. Implanted regions yield different resonance frequencies corresponding to the specific area where the core is precessing. We thus experimentally demonstrate the realization of multiple resonance frequencies in a single magnetic disk and support our results with micromagnetic simulations. Furthermore, we show that when exciting the vortex core dynamics in a non-linear regime, the lineshape of the rectified dc signal reveals a resonance peak splitting which depends on the excitation amplitude. Using micromagnetic simulations, we show that at high excitation power the peak splitting originates from the nanosecond time scale quasi-periodic switching of the vortex core polarity. When using lock-in detection, where the rectified voltage is integrated over a ms time scale, we find that the net signal detected between the two resonant peaks for a given range of parameters cancels out. The results are in agreement with previously reported effects of the in-plane static field magnitude on the gyration dynamics, complement them by a detailed analysis of the effects of the rf current amplitude and the azimuthal angle of the in-plane bias magnetic field, and also provide an alternative explanation for the peak splitting.

References

[1] D. Suess *et al.*, Nat. Electron. **1**, 362-370 (2018)
[2] W.H. Rippard *et al.*, Phys. Rev. Lett. **92**, 90-93 (2004)
[3] C. Behncke *et al.*, Sci. Rep. **8**, 186 (2018)
[4] M. Romera *et al.*, Nature **563**, 230-234 (2018)
[5] D. Silver *et al.*, Nature **550**, 354-359 (2017)
[6] L. Ramasubramanian *et al.*, ACS Appl. Mater. Interfaces **12**, 27812 (2020)

Quantum imaging of antiferromagnetic and ferroelectric textures

Prof. Christian Degen

Department of Physics, ETH Zurich, Switzerland

Diamond has emerged as a unique material for a variety of applications, both because it is very robust and because it has defects with interesting properties. One of these defects, the nitrogen-vacancy center (NV center), has a single spin associated with it that shows quantum behavior up to room temperature. Our group is harnessing the properties of single NV centers for high resolution magnetic sensing applications.

In this talk, I will introduce the basic technology and concepts and emerging applications of diamond-based quantum sensors. I will discuss the challenges in the fabrication of high-quality diamond probes and their integration into scanning probe microscopy systems. I will then present illustrative examples of applications in nanoscale magnetism, including the imaging of antiferromagnetic domains and domain walls. I will conclude with an outlook on the simultaneous imaging of electric and magnetic fields in piezoelectric and multiferroic materials.

Superconducting spintronics: open challenges and new materials platforms

R. Hartmann[1], A. Spuri[1], Z. Salman[2], Y. Paltiel[3], O. Millo[3], W. Belzig[1], E. Scheer[1], and A. Di Bernardo[1]

[1]Universität Konstanz, Konstanz, Germany
[2]Paul Scherrer Institute, Villigen, Switzerland
[3]The Racah Institute of Physics, Jerusalem, Israel

The generation of spin-polarized (spin-triplet) Cooper pairs of electrons at the interface between superconductor (S) and ferromagnet (F) materials has been demonstrated by various groups over the past two decades [1-5]. These experiments have paved the way for the research field currently known as superconducting spintronics (superspintronics) – which aims at exploiting spin-triplet superconducting currents in S/F hybrids to do spintronics with low-energy dissipation.

Technological applications based on superspintronics, however, appear still difficult to develop. One reason for this is because spin-triplet pairs must be driven out of equilibrium to do work such as, for example, exerting spin-transfer torque on a F. A second reason is related to the limited number of functionalities and forms of control which superspintronic devices currently have.

In this talk, I will describe the current challenges and open questions that superspintronics is facing. I will then present some recent results obtained by our group that suggest the possibility of generating spin-triplet pairs using material systems different the conventional three-dimensional (3D) S/F thin film multilayers used to date. The superspintronic systems that we are investigating include chiral molecules coupled to S materials [6] and 2D van der Waals heterostructures. These systems are not only interesting from a fundamental point of view, but also because they can help engineer superspintronic devices with novel functionalities and forms of control.

References

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3. A. Di Bernardo, S. Diesch, Y. Gu, et al., Nat. Commun. **6**, 8053 (2015).
4. S. Diesch, P. Machon, M. Wolz et al., Nat. Commun. **9**, 1 (2018).
5. A. Di Bernardo, Z. Salman, X. L. Wang et al., Phys. Rev. X **5**, 041021 (2015).
6. H. Alpern, M. Amundsen, R. Hartmann et al., Phys. Rev. Mater. 5, 114801 (2021).

Topology for energy efficient spintronics and energy conversion

Claudia Felser

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(e-mail: felser@cpfs.mpg.de)

Topology, a mathematical concept, recently became a hot and truly transdisciplinary topic in condensed matter physics, solid state chemistry and materials science. All 200 000 inorganic materials were recently classified into trivial and topological materials, such as topological insulators, Dirac, Weyl and nodal-line semimetals, and topological metals [1]. More than 25% of all materials host topological bands around the Fermi energy. Beyond the single particle picture, we have identified first antiferromagnetic topological materials [2]. Experimentally, we have realized ferromagnetic materials, examples are Co_2MnGa and $Co_3Sn_2S_2$. Surprisingly all crossings in the band structure of ferromagnets are Weyl nodes or nodal lines [3]. Mn_3Sn and $YbMnBi_2$ are examples of non collinear antiferromagnetic Weyl semimetals, which show giant values for the anomalous Hall and Nernst effect [4]. In the context of real space topology, skyrmions and antiskyrmions are a possible new direction for new data storage [5]. Our goal is to identify new quantum-materials for highly efficient spintronics, quantum computing and energy conversion.

1. Bradlyn et al., Nature 547 298, (2017), Vergniory, et al., Nature 566 480 (2019), Vergniory, et al., Science accepted arXiv:2105.09954.
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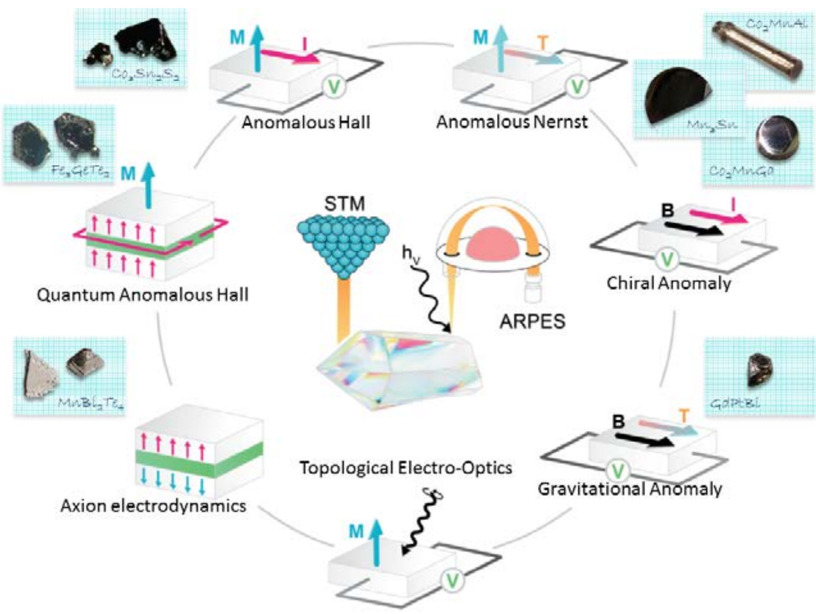
3. Liu, et al. Nature Physics 14, 1125 (2018), Belopolski, et al., Science 365, 1278 (2019), Guin, et al. Advanced Materials 31 (2019) 1806622, Liu, et al., Science 365, 1282 (2019), Morali, et al., Science 365, 1286 (2019)
4. Pan, et al., Nature Materials 21 (2022) 203, Kübler and Felser, EPL 120 (2017) 47002 and EPL108 (2014) 67001, Nayak, et al. Science Advances 2 (2016) e1501870
5. Nayak et al., Nature 548 (2017) 561



Manipulating topology of massive Dirac Fermion with scalar potential

S. Ghosh[1,2], **Y. Mokrousov and S. Blügel**[1]

[1]*Forschungszentrum Jülich Germany*
[2] *Johannes Gutenberg University Mainz Germany*

Topology is one of the central aspects of modern spintronics due to their connection to different physical observable and transport properties. In spite of immense mathematical study on characterization of topology, their physical origin remains elusive. In this presentation I am going to show how one can manipulate non-trivial topological feature using a simplified 2x2 Dirac system. I'll show how the topological feature is connected to the '*mass*' of the system and how one can achieve a topological phase transition with a simple scalar potential. This is also reflected into their bulk transport properties. This mechanism can also be applied in to a quasi-one-dimensional system to tune the quantized edge channels and associated transport properties.

References

[1] S. Ghosh, Y. Mokrousov and S. Blügel arXiv: 2204.06412 [http://arxiv.org/abs/2204.06412].

Gradient magnetoelasticity: tailoring and manipulation of antiferromagnetic textures

O. Gomonay[1]

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

Nowadays antiferromagnets are considered as important constituents of the spintronic devices. They show fast magnetic dynamics and can be effectively manipulated by the electric current or laser pulses. Many of technologically attractable antiferromagnets also show strong magnetoelastic effects, which can prevail over the direct spin-torque mechanism [1] and can be used for control and manipulation of the devices. However, an important prerequisite of such thermomagnetoelastic effects is inhomogeneous distribution of strains. In this presentation we discuss the effects associated with the strain gradients that appear in antiferromagnetic devices due to the clamping by nonmagnetic substrate, patterning, or current/temperature gradients. Following the ideas of Kléman [2] we treat magnetic inhomogeneities as a potential source of magnetoelastic defects associated with incompatibility (break of continuity) of the spontaneous strains (see Fig. 1). Incompatibility, treated further as a magnetoleastic charge, -- is a source of a long-range strain field that controls distribution of antiferromagnetic domains and orientation of the domain walls, modifies local magnetic anisotropy, and can create additional torques at different time-scales. Inspired by the gradient elasticity approach [3] we generalize it to include magnetoelastic effects and apply it to interpretation of the observed magnetic textures in different antiferromagnets relevant for spintronic applications. Our findings open new ways to manipulate antiferromagnetic textures by proper tailoring of the magnetic and magnetoelastic gradients.

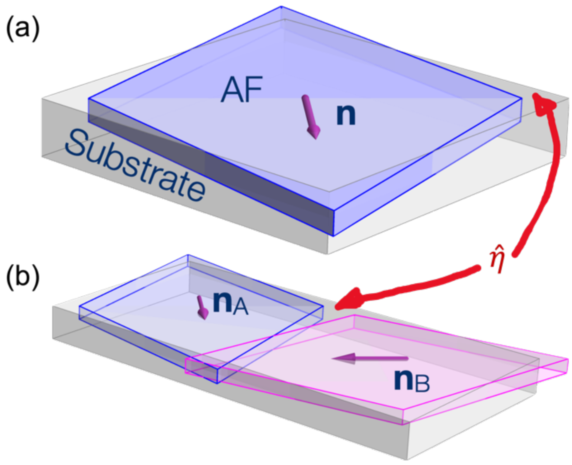


Fig.e 1: Incompatibility $\hat{\eta}$ induced by the magnetic inhomogenuties between (a) antiferromagnetic layer and substrate; (b) between two domains

References

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Direct-write nanofabrication with focused electron beams for 3D nano-magnetism

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Three-dimensional (3D) magnetic nanostructures enable the magnetization to orientate itself into three dimensions mediated by additional degrees of freedom and hence allowing complex spin configurations which can lead to novel magnetic phenomena. Such exciting tailored and designed structures can open the door for addressing fundamental questions and potential novel applications in magnetism. The exploration of this field has just begun with improvements in fabrication and characterization methods. A growing number of examples have already been demonstrated, such as complex 3D tetrapod arrays [1], arrays of multi-axial nanocubes and nanotrees [2], as well as more complex structures [3]; see [4] for a recent review.
In this contribution focus will be on recent advances in 3D nanofabrication by direct-writing using focused electron beam induced deposition (FEBID) [5]. FEBID is a unique and highly flexible direct-write nanofabrication approach. It is based on the electron-induced dissociation of a previously adsorbed precursor gas in the focus of an electron beam typically provided by a scanning electron microscope. After a brief introduction to the methodology controlling the growth of nano-scale 3D structures starting from a CAD model – including modelling of the growth process – very recent results on applications of FEBID in nano-magnetism are presented. A novel FEBID/CVD approach suitable for the fabrication of hollow, multi-segment or multilayer magnetic 3D structures is presented for the first time [6].

References

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[6] F. Porrati et al., Selective chemical vapor deposition on direct-write 3D nano-architectures, to be submitted (2022)

Chiral Material Sciences

K. Inoue[1, 2, 3]

[1]Chirality Research Center (CResCent), Hiroshima University, Hiroshima, Japan.
[2] WPI- International Institute for Sustainability with Knotted Chiral Meta Matter (SKCM[2]), Hiroshima University, Hiroshima, Japan.
[3]Department of Chemistry, Hiroshima University, Hiroshima, Japan

Chirality is a scale-free concept that is valid from subatomic-scale to cosmic sizes. It is therefore thought to have similar effects at various scales and/or physical properties and even be transferred between different scales and/or physical properties. It can be defined in terms of at least two completely different phenomena: shape and motion. Chirality of shape, also called "handedness", derives from the definition by Lord Kelvin. Chirality of motion describes, for example, the motion of right-handed and left-handed screws, and was defined by Professor Lawrence Barron [1]. Recent studies of chiral magnetic materials [2] have revealed a strong connection between the chirality of shape (crystals) and the chirality of motion. As a result of this coupling, the magnetic moment become chiral aligned in chiral magnets crystals. It has been found that structures of spins with various topologies are then stabilized. [3] These structures contain many twists and knots, and it is becoming clear that the twist directions and knots are also chiral.

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Enhancing Electron Correlation at a 3d Ferromagnetic Surface: a Pathway to Access Novel Material Properties?

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Understanding the physics of interfaces that involve ferromagnetic transition metal surfaces is pivotal for designing novel spintronic devices with exotic properties and unmatched performances [1]. By combining spin-resolved momentum microscopy with state-of-the-art theoretical calculations that go beyond the one-electron approximation, we unveil that a chemisorbed oxygen layer strongly enhances electron correlation at an iron (Fe) surface [2]. As a result of this enhancement, the Fe d-bands near the Fermi energy are severely narrowed and their exchange splitting is reduced. Furthermore, electronic correlations lead to a spin-dependent broadening of the adsorbate-related bands at higher binding energies, due to the influence of emerging satellite features that are a direct manifestation of many-electron behavior.

Overall, adsorption and interface formation can be used to access different intermediate correlated regimes, which would otherwise not be accessible and possibly offer unique electronic and magnetic properties. Our results show that the concepts developed to understand the physics and chemistry of adsorbate-metal interfaces, ubiquitous in spintronics and catalysis, need to be reconsidered with many-particle effects being of tremendous importance, as they may affect chemisorption energy, spin transport and magnetic order, and even play a key role in the emergence of ferromagnetism at interfaces between non-magnetic systems [3].

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Imaging Nanometer-Scale Skyrmion (De)formation Dynamics

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In recent years, the current- and laser-induced manipulation of magnetic skyrmions in ferromagnetic multilayer systems has seen great advances in generating, annihilating, and moving skyrmions [1–3]. By predefining the magnetic anisotropy landscape employing He^+-ions, we have recently introduced a new technology for deterministic generation and motion of magnetic skyrmions with nanometer-scale control [4]. This approach of magnetic nanopatterning allows us to transform the generation of magnetic skyrmions into a repeatable process. The enhanced spatial control opens perspectives towards technological application of skyrmions and provides a promising platform for repeatable pump–probe experiments to follow skyrmion dynamics on a fundamental level.
Here, we show first results of time-resolved imaging of the magnetization dynamics induced at an artificial nanometer-scale anisotropy defect by current-generated spin–orbit torque in a chiral ferromagnetic multilayer. Similar defects have previously been used as nucleation sites [2,4,5] and they strongly influence skyrmion trajectories [6]. In concert with micromagnetic simulations, we observe very different response of the local spin system to the nanosecond-pulsed excitation in dependence of the applied field. The effects comprise skyrmion shedding [5], skyrmion formation [2,4,5] and more complex skyrmion instabilities.
Based on our results, we aim to understand the magnetization dynamics at an artificially created nucleation site within the first instances during and after excitation. Understanding the skyrmion formation process, transiently involved textures and fundamental speed and size limits might enable further research on topological textures in general.

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Interaction parameters in magnetic 2D systems from symmetric invariants

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The electronic properties of 2D materials hosting complex magnetic order can have crucial implications for information storage and processing applications. At the heart of the complexity in these materials is the interplay of external fields, fluctuations and electronic structure with the magnetic properties. In this work, we are aiming to uncover the direct implications that changes in the magnetic texture have on the electronic characteristics of the system. We develop an expansion in terms of the texture's symmetric invariants and compare to data obtained from Heisenberg Hamiltonians [1], tight-binding (TB) calculations [2] or possibly even density functional theory (DFT) calculations by employing a machine learning (ML) algorithm for the fitting task. Specifically, this enables us to identify the relevant interaction terms from the expansion to the total energy, since there is a diverse palette of ML fitting algorithms aiming at sparse models with the smallest possible number of coefficients, including regularized [3] and sequential approaches [4].

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Dynamics of solitons in antiferromagnets

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Magnetic solitons, such as skyrmions, exist in antiferromagnets for essentially the same reasons as in ferromagnets. Studies of antiferromagnets have been hampered by the difficulty in observations due to the lack of a generated magnetic field. The situation is changing in the last years as experimental techniques become available that allow for observations down to a few nanometers scale.

We present a model for antiferromagnetic order including the Dzyaloshinskii-Moriya (DM) interaction. We study antiferromagnetic skyrmions described via the Néel vector, that is the appropriate order parameter. We explain that the chiral DM interaction is crucial also for the dynamics of solitons, in addition to its role in their stabilization.

In the first example [1], we show that skyrmions in chiral antiferromagnets can be traveling as solitary waves (as in Fig. 1). The velocity has a maximum value that depends on the DM parameter and the relativistic behaviour is related to a topological (spiral) phase transition. It is found analytically and shown numerically that the solitonic behavior of skyrmions in antiferromagnets is in stark contrast to the dynamical behavior of their ferromagnetic counterparts.

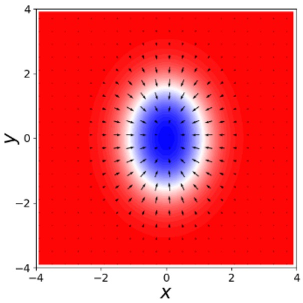

Figure 1. Néel vector for a traveling skyrmion.

In the second example [2], we study breathing oscillations of skyrmions in the nonlinear regime. We present an adiabatic approximation and derive a formula for the breathing potential energy. An unusual feature of the potential is that it allows for skyrmion collapse and subsequent annihilation events (an example is shown in Fig. 2). The process is efficient when the skyrmion is only mildly excited so that its radius initially grows, while the annihilation event of the topological texture is eventually induced by the internal breathing dynamics.

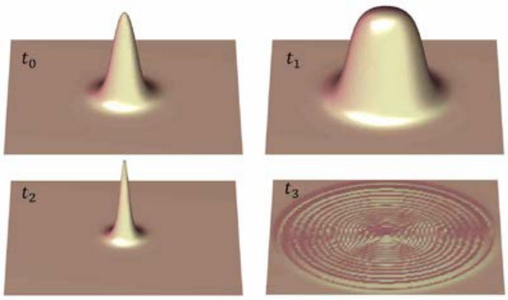

Figure 2. Skyrmion annihilation event via breathing. The third component of the Néel vector is shown.

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Nanomagnets for electric dipole spin resonance and spin–photon coupling

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We will cover one of several on-going works involving magnetically ordered, condensed matter systems used in quantum devices. Spin qubits hosted in double quantum dots can be operated by interaction with microwave radiation, in a scheme called electric dipole spin resonance, where the spin character of an energy level transition is mixed with a delocalized dipole character. This allows for a much stronger coupling of the spin to the electric component of a photon mode than what can be achieved with the magnetic component [1]. This scheme usually integrates the quantum dots inside an inhomogeneous magnetic field obtained from nanoscale ferromagnetic electrodes. While the strength of this inhomogeneous magnetic field directly determines the coupling rates, only few corresponding magnet geometries and materials have been explored [2-5].

We have investigated how to maximize the inhomogeneous stray fields, by reverting to the fundamentals of nanomagnetism to design elements as close as possible to ideal field gradient sources. We develop on all possible geometries for field, longitudinal and transverse field gradients and identify configurations maximizing them. These designs are further validated with micromagnetic simulations, considering actual material properties, of external fields that ensure magnetic saturation of the devices. We will also discuss realization with domain-wall systems, and introduce experimental constraints and progresses.

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Efficient Spintronics Utilizing The Chiral Induced Spin Selectivity(CISS) Effect

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The Chiral Induced Spin Selectivity (CISS effect) based spintronics technology has the potential to overcome the limitations of other magnetic-based memory technologies and to facilitate the fabrication of inexpensive, high-density memory and other spintronics elements [1]. Utilizing the CISS effect, we demonstrated a simple spin based nano magnet-less optical and electrical memory [2,3]. When chiral molecules are adsorbed on the surface of thin ferromagnetic film, they induce magnetization perpendicular to the surface, [4] on s wave superconductor a triplet is induced [5]. CISS effect based devices were scaled down to the 30nm size replacing the continuous ferromagnetic layer with magnetic nano platelets [6,7]. ALD Chiral oxides can supply 99% spin polarization [8]. In may talk I will show the advantages of CISS-based spintronics, and also present the missing ingredients for realizing quantum and classical CISS-based technology.

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Nonlinear magnonics for unconventional computing

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Coherent spin waves [1] are ideal candidates for wave-based computing since they offer pronounced nonlinear properties, wavelengths scalable to the nanometer range and GHz clock rates compatible with CMOS-based circuits. Numerous linear and nonlinear magnonic building blocks have been demonstrated. In this context, unconventional ways to process and analyze data like brain-inspired computing are a perfect match to the advantages offered by the magnonic system [2].
In my presentation, I will focus on the use of nano- and micro-scaled nonlinear magnonic devices made of insulating ferrimagnetic structures. For coherent magnons, the nonlinear shift of the magnon wave vector is the most robust nonlinear phenomenon. For nanoscale devices, this shift can be greatly enhanced since magnon instabilities can be efficiently supressed. I will discuss how this nonlinear shift can be used to design devices with build-in features like activation functions, amplitude self-normalisation [3] and short-time all-magnon memory. In addition, I will demonstrate how fast exchange spin waves in the novel material Ga-substituted Yttrium Iron Garnet [4], create “magnonic spikes” which can be used to build spiking neural networks.

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Magneto-thermal transport in compensated magnets

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Spintronics with antiferromagnets is a quickly developing research direction and in the last decade many spintronics phenomena were demonstrated in magnetically ordered systems with vanishing magnetization [1,2]. In particular the non-collinear antiferromagnets are a fascinating class of materials showing important phenomena such as the anomalous Hall effect [3] and the anomalous Nernst effect [4]. In the first part of talk I will discuss transversal magneto-thermal transport properties of two representatives of non-collinear systems: Mn_3Sn [5] and Mn_3NiN [6] thin films.

Very recently also the collinear magnets were predicted to exhibit the anomalous Hall effect [7] arising from their spin and crystal symmetry and I will discuss an experimental verification in Mn_5Si_3 thin film [8]. In this material, the anomalous Nernst effect can be equally present and a first experimental indication of the effect in a collinear magnet will be discussed [9].

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Magnetic garnets for spintronics

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Magnetic insulator thin films provide unique functionality in spintronic, magnonic, and magnetooptical devices such as magnetic memory, magnetic logic, and photonic integrated circuits. Iron garnets exemplified by yttrium iron garnet are ferrimagnetic insulators with a wide range of properties manipulated by cation substitution. Films and multilayers of rare earth and Bi-substituted garnets and garnet/metal heterostructures can be grown with tunable magnetic anisotropy, damping, and compensation temperatures. These materials reveal a Dzyaloshinskii-Moriya interaction that yields chiral domain walls in rare earth garnets; and high speed domain wall motion driven by both spin orbit torques from a current in a Pt layer and by spin waves excited by an r.f. antenna in Bi-garnets. Iron garnets also exhibit magnetooptical activity and high transparency in the infrared, and can be used in integrated magnetooptical isolators to control the flow of light in photonic circuits. We will focus on the role of cation site occupancy in determining the properties of garnets and other complex oxides, and we will also describe a new class of multiferroic perovskites where ferroelectricity is introduced using antisite defects.

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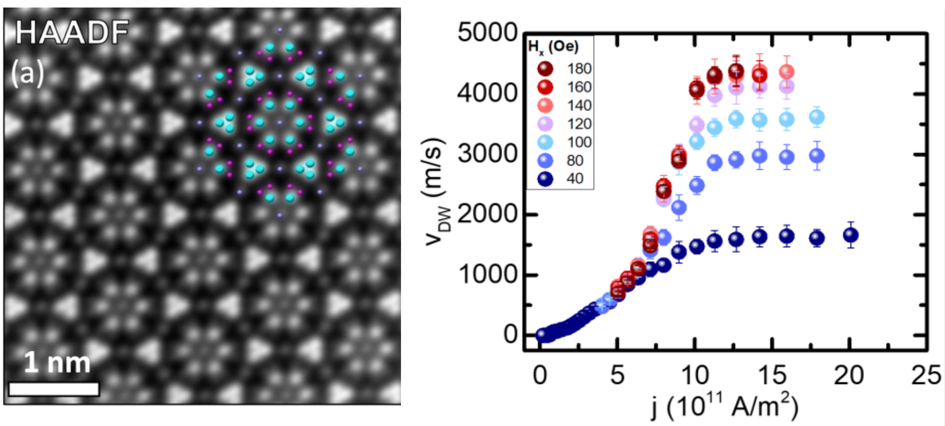

Left: High resolution plan view electron micrograph of a (111)-oriented terbium iron garnet film. Blue: rare earth; purple: Fe sites. Right: domain wall velocity *v* reaches 4.3 km/s in Bi-substituted yttrium iron garnet, driven by a current *j* in a Pt overlayer, for different in-plane fields.

Unconscious bias: how it impacts careers in science and how to mitigate this influence

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We all are subject to unconscious bias - if you don't know how biased you are, test yourself [1]. Therefore bias severely conditions our own career and that of others, and knowing about it is crucial to become better professionals in science. The aim of this talk [2] is to give everyone the means to recognize unconscious bias in their professional environment and recipes to work against it. I shall discuss how the four most common forms of unconscious bias impact the careers in science: performance bias, performance attribution bias, maternal bias and the competence/likeability trade-off.

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[1] https://implicit.harvard.edu/implicit/
[2] This talk was inspired by the facebook video http://managingbias.fb.com/

Altermagnetism: spin symmetry foundations and unconventional spintronics effects

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Different phases of matter can be distinguished by symmetry, order parameters and topological properties [1]. In this talk, we will discuss the classification of magnetically ordered crystals according to recently studied spin symmetries, which consider pairs of operations in spin and crystal space [2]. Remarkably, spin symmetries reveal a third unconventional magnetic order that is sharply distinguished from more conventional ferromagnets and antiferromagnets [2]. The third magnetic order, called altermagnetic, is characterized by an alternating spin order in electronic momentum space in the d,g or i-wave angular form. Altermagnetic momentum space order realizes the previously elusive combination of time-reversal symmetry breaking and spin-compensation, and thus represents the long-sought magnetic analogue of unconventional superconductivity [2]. We will illustrate that the unique altermagnetic properties are arising from an anisotropic spin density in real space (see figure) [2,3].

In the second part of the talk, we will discuss theoretically proposed unconventional and promising applications of altermagnetism in spintronics, including giant magnetoresistance and anomalous currents [3-7]. We will explain that the recently reported unconventional anomalous Hall current in Ruthenium Dioxide provides experimental evidence for the theoretically predicted altermagnetic effect [3,6,7]. Finally, we highlight the rich research opportunities allowed by the >200 identified candidate materials ranging from metals to insulators and superconductors.

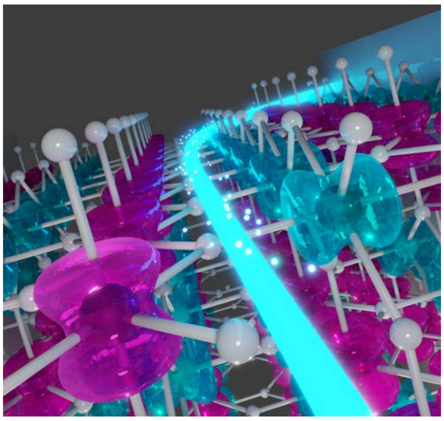

Figure 1 Magnetisation densities in Ruthenium Dioxide and visualization of anomalous Hall current in (110) crystallographic plane.
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Concepts from multiferroics that might be useful for spintronics

Nicola Spaldin

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We explore how concepts developed in the context of magnetoelectric multiferroics -- in which the magnetism is modified using an electric *field* -- might be relevant for the field of spintronics, in which the magnetism is modified using an electric *current*. First, we use the magnetoelectric multipoles, which are established as the order parameter in magnetoelectric multiferroics, to clarify the relationship between the current-induced spin polarization in non-centrosymmetric metals and the linear magnetoelectric response in non-centrosymmetric insulators. We then show how higher-order magnetic multipoles are convenient for unifying the diverse behaviors of unconventional centrosymmetric antiferromagnets, including piezomagnetism, surface magnetization and non-relativistic spin-splitting. Finally, we provide a simple formalism for understanding how polar materials that are non-magnetic in real space can have a hidden antiferromagnetic, and hence spintronic, behavior in reciprocal space.

Non-volatile spin-orbit torque driven antiferromagnetic memristor

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Today's digital mass magnetic data storage is based on switching and detecting energetically degenerate ferromagnetic ground states with opposite magnetization, separated by a sufficiently high energy barrier to preserve the non-volatility of the stored data for decades. Recently, antiferromagnetic systems have been of increasing interest as a possible robust and energy-efficient alternative to ferromagnetic data storage due to their insensitivity to magnetic fields and their switching dynamics, which is typically orders of magnitude faster than in ferromagnets. However, opposite magnetic states in collinear antiferromagnets with zero net magnetic moment are considered indistinguishable, and switching between orthogonal states in cross-shaped structures is found to be unstable, as the switching process is typically followed by a stretched exponential decay [1-3].
In this talk I will show that in compensated antiferromagnets with combined space-inversion and time-reversal symmetry both switching between and detection of nonvolatile states with oppositely oriented Néel vectors can be readily realized by current-induced relativistic spin-orbit fields in a simple two terminal device [4,5]. Moreover, instead of writing and reading only digital "0" and "1" states corresponding to two fully polarized antiferromagnetic states, we also can achieve non-volatile analog storage by highly reproducible switching between stable multi-domain states, realizing a memristor functionality in an antiferromagnet.

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Abstracts of Posters

(in alphabetical order)

Magnetization dynamics in hybrid ferromagnetic/antiferromagnetic systems

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The significant difference in the magnetization dynamics of ferromagnetic (FM) and antiferromagnet (AFM) materials could potentially be exploited in applications integrating AFM materials in high-frequency spintronic devices. A promising approach to enhance the FM spin dynamics frequencies and control FM spin-wave dispersions might be the combination of FM and AFM thin-film layers with interfacial exchange coupling. We study the magnetization dynamics of the $Mn_2Au/Ni_{80}Fe_{20}$ thin film bilayer system. This system allows us to control the Mn_2Au Néel vector orientation with moderate in-plane external magnetic fields depending on $Ni_{80}Fe_{20}$ layer thickness [1]. Mn_2Au furthermore shows strong spin-orbit torque efficiency [2] making this system intriguing for all-electrical control of the magnetization direction. The $Ni_{80}Fe_{20}$ thickness is varied to study the effect of the $Mn_2Au/Ni_{80}Fe_{20}$ interface on $Ni_{80}Fe_{20}$ spin dynamics. Broadband ferromagnetic resonance and Brillion light scattering experiments reveal that interfacial exchange coupling causes an emergence of two enhanced resonance frequencies in $Ni_{80}Fe_{20}$, with zero-field resonance frequencies increased up to 40 GHz. Our theoretical model based on the modification of the spin-wave wavevector due to interfacial exchange coupling yields good agreement with the experimental observations.

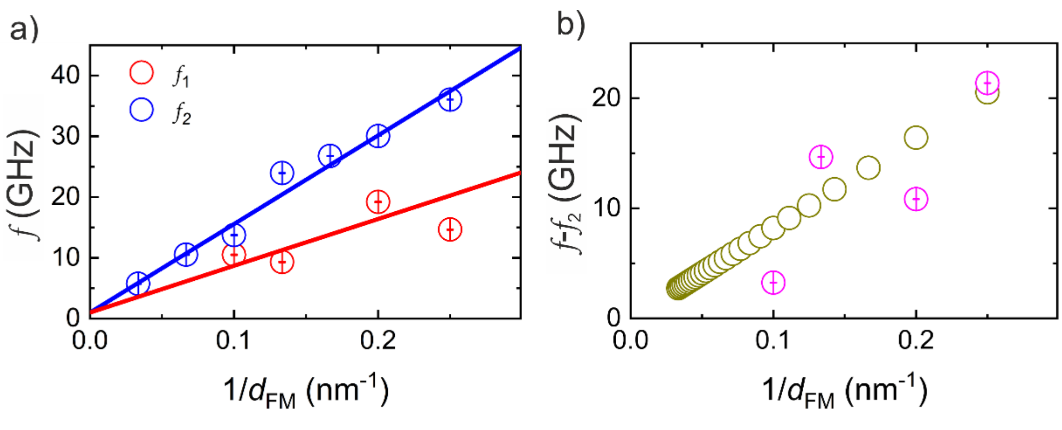

Figure1: a) Resonance frequencies (f_1,f_2) as a function of ($1/d$), where d is the thickness of $Ni_{80}Fe_{20}$. b). Numerically and experimentally obtained difference in resonance frequencies f_2 - f_1 vs. ($1/d$).

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Observation of nonreciprocal magnon Hanle effect

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The precession of magnon pseudospin about the equilibrium pseudofield, the latter capturing the nature of magnonic eigen-excitations in an antiferromagnet, gives rise to the magnon Hanle effect [1-5]. Its realization via electrically injected and detected spin transport in an antiferromagnetic insulator demonstrates its high potential for devices and as a convenient probe for magnon eigenmodes and the underlying spin interactions in the antiferromagnet. Here, we observe a nonreciprocity in the Hanle signal measured in hematite using two spatially separated platinum electrodes as spin injector/detector. Interchanging their roles was found to alter the detected magnon spin signal [6]. The recorded difference depends on the applied magnetic field and reverses sign when the signal passes its nominal maximum at the so-called compensation field. We explain these observations in terms of a spin transport direction-dependent pseudofield. The latter leads to a nonreciprocity, which is found to be controllable via the applied magnetic field. The observed nonreciprocal response in the readily available hematite films opens interesting opportunities for realizing exotic physics predicted so far only for antiferromagnets with special crystal structures.

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Transfer printing of GMR sensing elements for curved electronics

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During last years, touchless interaction between human beings and environments is attracting more and more attentions [1,2]. This opens a request for integration of electronic structures into more complex curved, flexible, or even living organism substrates for skin-like electronics, wearable health monitoring devices, virtual reality etc. Sensors based on giant magnetoresistance (GMR) effect are widely considered as a workhorse to address this demand. However, the fabrication of GMR multi-layer elements face many limitations (e.g., inappropriate to substrates with curved and/or rough surfaces) due to the layer thickness dependence of performance [3].

Here, we propose a transfer technique, which allows to overcome the aforementioned limitations. We demonstrate that a high-performance sensing elements can be transferred from flat polymer-based donor substrates to variable receiver surfaces with little loss of GMR performance (figure 1). Furthermore, such technique does not require any substrate deformation, temporary carriers or high-temperature processing methods, what prevents device damage.

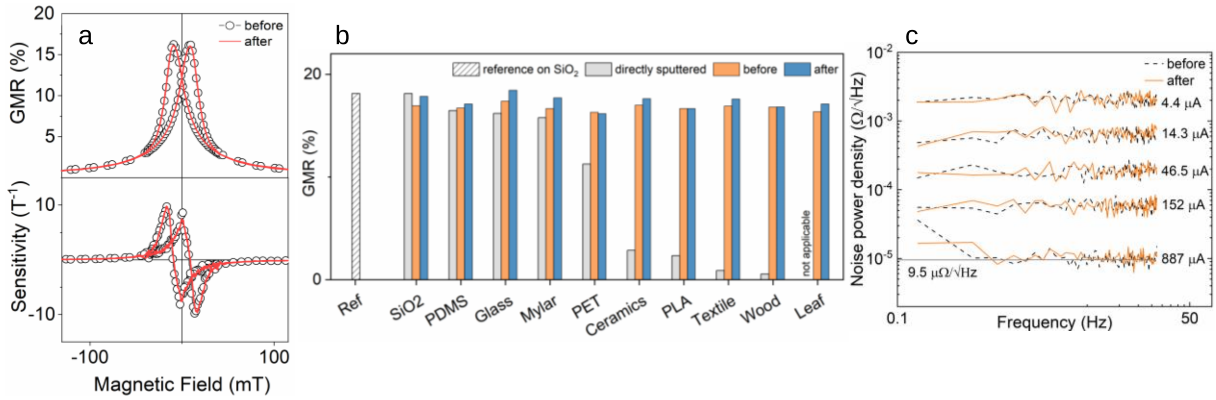

Figure 1: Characterization of GMR sensors before and after transfer: a) magnetoresistive sensitivity of sensor (transferred on PET); b) MR response of the sensors, transferred onto different substrates; c) noise signal of sensor

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Magnetic field-induced textures and phase transitions in antiferromagnetic spin chains: geometry-induced effects

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Easy axis antiferromagnets (AFMs) are robust against external magnetic fields of a moderate strength. Spin reorientation transitions in strong fields can provide an insight into more subtle properties of antiferromagnetic materials, which are often hidden by their high ground state symmetry. In curved intrinsically achiral AFM spin chains geometrical bends and twists provide helimagnetic responses, characterized as effective anisotropic and Dzyaloshinskii–Moriya-like (DMI) interactions [1].
Here, we address theoretically effects of curvature in achiral anisotropic ring-shaped AFM spin chains with even number of spins exposed to strong magnetic fields using the methodology of curvilinear magnetism. We identify the geometry-governed helimagnetic phase transition enabled in the spin-flop phase, which separates locally homogeneous (vortex) and periodic (onion) AFM textures [2, 3]. The curvature-induced Dzyaloshinskii–Moriya interaction results in the spin-flop transition being of the first- or second-order depending on the ring curvature. Spatial inhomogeneity of the Néel vector in the spin-flop phase generates the weakly ferromagnetic response in the plane perpendicular to the applied magnetic field [3]. In AFM spin chains possesing torsion, e.g. helices, these effects are enhanced by the inhomogeneity of local texture in the ground state. Our work provides further insights in the physics of curvilinear AFMs in static magnetic fields and guides prospective experimental studies of geometrical effects in the spin-chain nanomagnets.

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Flat bands in magnonic Lieb lattices

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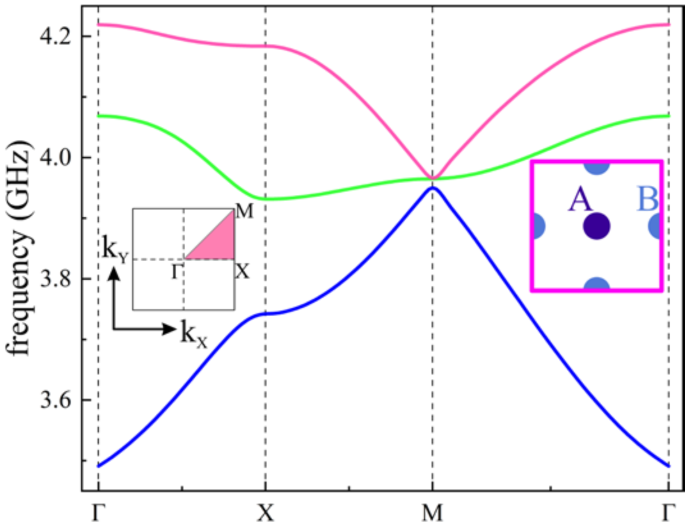

Figure 1. Dispersion relation obtained for magnonic Lieb lattice.

Magnonic crystals are promising structures for future application in spintronics and magnonics since their dynamical properties, described by dispersion relation for spin waves, can be tailored and tuned [1]. Despite keen interest in magnonic crystals [2], not all of their properties are discovered today. In our work, we demonstrate a new kind of localization due to the topological properties of magnonic crystals. In 1986, Bill Sutherland proposed the existence of flat bands by investigating certain Hamiltonians in a tight binding approximation [3]. Recently flat bands were considered in electronics and photonics [4] but there were no reports on the realization of the Lieb lattices in magnonics.

We proposed a perpendicularly magnetized (by field μ_0H=0.1 T) realistic magnonic structure consisting of a Ga-dopped YIG layer (of thickness 59 nm) with cylindrical inclusions (without Ga content) arranged in a Lieb lattice with a 250 nm period in case of basic configuration. We tailored the structure to observe, for the few lowest magnonic bands, the oscillatory and evanescent spin waves in inclusions and matrix, respectively. Such a design reproduces the Lieb lattice of sites (inclusions) coupled between each other (by the matrix) – see inset in Fig. 1. We present spectra and profiles of spin waves for types of Lieb lattices (differing in the complexity of unit cell), calculated by finite element methods in COMSOL.

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Magnetic properties of sputtered Terbium Iron Garnet thin films

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Recently, ferrimagnetic materials have become a platform of choice in the field of spintronics in view of the interesting dynamic behavior triggered in the vicinity of the magnetic compensation. At the compensation temperature (T_M), the system acts like an antiferromagnet and the efficiency of spin-orbit-torques is significantly enhanced [1-2]. In this work, we report the structural, magnetic, and spintronic properties of epitaxial terbium iron garnet (TbIG) films, a ferrimagnetic insulator with T_M close to room-temperature. The samples are deposited on various (substituted) GGG substrates by RF magnetron sputtering and high crystallinity is achieved at growth/annealing temperatures above 750 °C. The films display perpendicular magnetic anisotropy induced by compressive strain and tunable structural and magnetic properties with annealing conditions. Studying the temperature evolution of the anomalous Hall-effect (AHE) in Pt/TbIG heterostructures, allows to determine the compensation temperature of the ferrimagnetic ordering, that is found to be approximately ~200 K, some 50 K lower than in bulk. This is attributed to the Tb deficiency of the films corroborated by x-ray photoelectron spectroscopy measurements [4]. Controlling the ferrimagnetic ordering by tuning the composition is well reported in amorphous metallic alloys [3] but less investigated in epitaxial insulators and can be exploited in future spintronics experiments.

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Critical Behavior and Exchange Splitting in the Antiferromagnet Monolayer Mn on Re(0001)

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The strong progress in active antiferromagnets also renewed the interest in the origin of magnetic order in antiferromagnets depending on dimensionality and localization of magnetic moments. In the case of itinerant ferromagnets like Fe, Co and Ni, the temperature dependence of magnetic order has been explained by a one-electron finite temperature band theory, known as “Stoner theory”, where the exchange splitting Δex collapses at the Curie temperature. Instead, strong correlation effects included in the framework of the local band theory by local moments (Heisenberg model) lead to short-range spin order persisting even above T_C.

We investigated the temperature-dependent electronic structure of the anti-ferromagnetic fcc monolayer Mn on Re(0001) [1] using vacuum-ultraviolet momentum microscopy [2]. At T = 25 K the collinear, row-wise antiferromagnetic phase of the Mn monolayer results in a spin splitting of states. Density functional theory, being in good agreement with the experimental results, reveal the spin- and orbital projection of the observed electronic bands. The exchange splitting of a pair of bands decreases from 280 ± 10 meV at 25 K down to 185 ± 10 meV at the Néel temperature T_N = 75 ± 5 K. The exchange splitting remains constant for $T > T_N$. The persisting exchange splitting is attributed to a remaining short-range, fluctuating antiferromagnetic order.

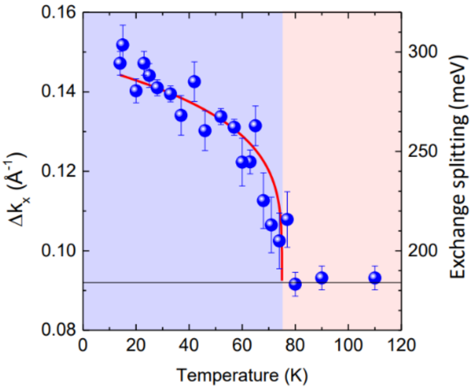

Fig. 1 Exchange splitting Δ_{ex} on the energy and Δk_{ex} on the momentum scale as a function of temperature. The full line corresponds to a fit to the function $\Delta_{ex}(T) = \Delta_{ex}(T_N) + \Delta_{ex}(0)(1-T/T_N)^{\beta}$ with the critical exponent β=0.5.

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Curvilinear phenomena in magnetization dynamics and in stray field

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In recent years, curvilinear magnetism is captivating due to the broad range of phenomena emerging in curved geometries that are appealing for developments in stretchable and magnetoelectric devices, microrobots, sensors, flexible memories and nanoelectronics [1-5].

These phenomena encompass exchange- and Dzyaloshinskii-Moriya (DMI)-induced interactions that typically result in topological magnetization patterning in thin shells, symmetry breaking, and pinning of domain walls [1-9]. Less attention is been paid though to the role of the curvilinear effects in the stray field, and in the magnetization dynamics [4]. For application development, spin-orbit torques provide an alternative way to manipulate magnetic domain walls and magnetization [10, 11] with reduced power consumption.

Here we present first results in stray field calculation in curvilinear geometries, and domain wall tilts in single 100 nm wide 2 nm thin periodically corrugated strips of CrOx/Co/Pt with average curvature of 0.06 nm^{-1}.

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Skyrmionics for neuromorphic computing

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The recent exponentiation of artificial intelligence (AI) applications has underscored a pressing need to develop computing paradigms which go beyond conventional architectures with enhanced performance and efficiency. In neuromorphic computing, inspiration is drawn from the biological brain, in which neurons and synapses fulfilling the roles of computational and adaptive memory elements respectively [1]. Spintronics offers an attractive approach to neuromorphic computing, where artificial neurons and synapses may be built from nanoscale magnetic systems. In particular, magnetic skyrmions have been identified [2-4] as highly promising candidates for encoding synaptic weights in neuromorphic systems, owing to their nanoscale size, non-volatility, and high mobility.

In this work, we propose a multilayered nanosynapse device based on skyrmion transport, and demonstrate numerically that it is possible to achieve both long-term potentiation and long-term depression of the synaptic weight at room temperature [5]. By tailoring the device geometry and the number of multilayer repeats, we show that it is possible to optimize the synaptic resolution, and thus the number of distinct states that can be encoded. The performance of the device in the context of a spiking neural network (SNN) is then tested through simulations, utilizing spike-timing-dependent plasticity (STDP) as the training rule. We demonstrate that with the optimized synaptic resolution, it is possible to achieve a classification accuracy of 98.6 % in a deep SNN operating on the Modified National Institute of Standards and Technology handwritten data set.

We furthermore present the preliminary stages of work to fabricate and characterise the proposed nanosynapse device, using a combination of X-ray and scanning probe microscopy techniques.

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Cryogenic NV Magnetometry applied to Multiferroics

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Imaging weak magnetic fields using the electronic spin of a nitrogen-vacancy (NV) defect in diamond is a well-established, very versatile technique for studying magnetic materials, mainly due to exceptionally long spin-coherence times [1]. The quantum sensor based on the NV center has been an active field of research, widening its capabilities to obtain information on weak magnetic fields with sensitivities in the nanotesla regime and nanometric resolution. In recent years, further uses of these sensors, such as gradiometry techniques, electric-field imaging or its extension towards cryogenic temperatures have been explored with promising results [2-4].

A combination of mentioned techniques could be of great interest towards understanding the fundamental nature of more complex systems, such as those present in multiferroics. There, more than one ferroic order, for instance, ferroelectric and antiferromagnetic, coexist [5]. The interest in such systems relies on their potential use for more efficient, smaller, and reliable magnetic devices, for instance, a low energy switching, non-volatile nanoscale magnetic memory [6].

In this project, we want to understand the relation between domain structures of the different phases, studying their interlocking mechanisms [7]. Imaging magnetic and electric domains of such materials simultaneously, which is one of the project's main goals, will be a breakthrough that pushes our understanding of the physics underlying those systems a step further.

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Direct evidence of superdiffusive terahertz spin current arising from ultrafast demagnetization process

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Using element-specific measurements of the ultrafast demagnetization of Ru/$Fe_{65}Co_{35}$ heterostructures, we show that Ru can exhibit a significant magnetic contrast (5% asymmetry) resulting from ultrafast spin currents emanating from the demagnetization process of the FeCo layer as shown in Fig. 1(a, b) [**1**]. We use this magnetic contrast to investigate how superdiffusive spin currents are affected by the doping of heavy elements in the FeCo layer. We find that the spin currents are strongly suppressed by Re doping, in accordance with the theoretically predicted terahertz spin current in Ru, utilizing the superdiffusive spin transport model as shown in Fig. 1 (c,d) [**1**].

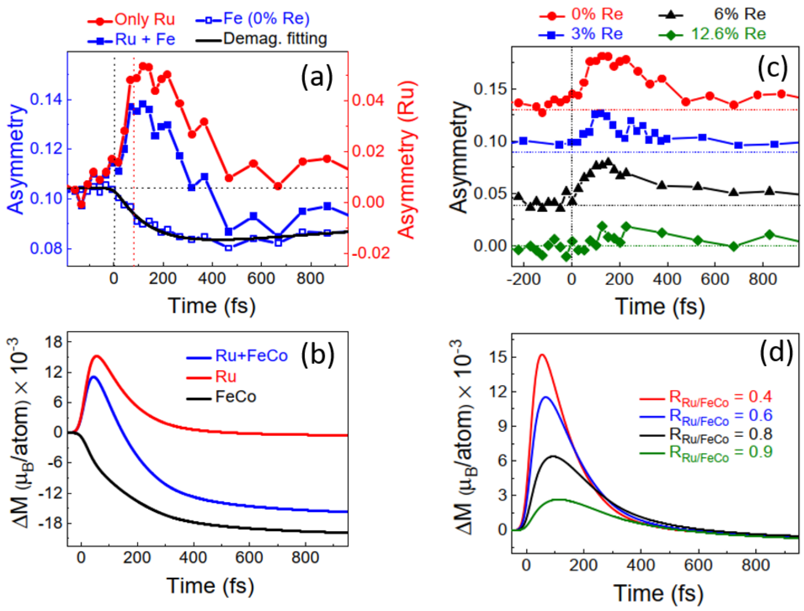

Fig. 1. (a) The time-dependent magnetic asymmetry measured at the Fe and Ru edges for the undoped sample. (b) Time-dependent magnetization in Ru and FeCo, computed with the superdiffusive transport model. (c) Ultrafast magnetization dynamics of Ru in $Fe_{65}Co_{35}$ films with different Re doping. (d) Computed time-dependent magnetization in Ru for different reflection coefficients at the Ru/FeCo interface.

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Spontaneous emergence of spin-wave frequency combs mediated by vortex gyration

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Due to their intrinsic nonlinear behavior, magnons pose an excellent model system for studying a variety of nonlinear physical phenomena. Researchers in the field discuss fundamental physical questions but also evaluate the potential for technical applications such as hardware implementations of neural networks. Therefore, it is of great interest to find ways to manipulate and control nonlinear magnon interactions. Recently, it has been shown that four-magnon scattering can be stimulated into specific frequency channels and a cascade of the stimulation processes leads to a spin-wave frequency comb in CoFe stripes [1].
Here, we extend the formation of spin-wave frequency combs to another confined system, a magnetic vortex. The magnetic vortex shows rich spin-wave dynamics like the formation of whispering gallery magnons [2] and non locally induced three-magnon scattering [3], all with frequencies in the GHz range. Additionally, there is the low frequency gyration of the vortex core itself. The combination of these dynamics on two different time scales inside magnetic vortices, results in the generation of spin-wave frequency combs with their spacing given by the vortex gyration frequency.
Using Brillouin light scattering microscopy, we show that large amplitude excitations of spin waves purely in the GHz range can induce a gyration of the vortex core and vice versa, which leads to the formation of frequency combs. In addition to the spontaneous emergence of the comb, it is also possible to force the gyration using a second microwave source and, thereby, change the spacing and the intensities of the sidebands.
The authors acknowledge financial support from the Deutsche Forschungsgemeinschaft within program SCHU 2922/1-1.

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Current driven skyrmion movement and their electrical detection in Ta/CoFeB/MgO

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Magnetic skyrmions, the two-dimensional topological protected round spin structures, have a strong potential for implementation into future storage devices as information bits e.g., in the conceptual racetrack memory [1].

For this purpose, the dynamics of skyrmion motion and their detection is an essential tool. Skyrmions can be generated in Ta/CoFeB/MgO layer stacks at room temperature. To reach the desired conditions for skyrmion creation, a narrow CoFeB thickness region must be achieved. The sputtering method offers the possibility to tailor this narrow layer thickness window, by adjusting the angle between the material source and the substrate. This enables thickness gradients across the fabricated samples in the picometer range and thus a playground for skyrmion investigation. Using current pulses in the nanosecond range, it is possible to move the skyrmions with current densities of 10^{12} – 10^{13} A/m^2. The dynamic trajectories hint to the skyrmion-Hall-effect [2] and superdiffusion [3], requiring special racetrack design. The skyrmion-Hall-effect results from the skyrmion topology and the superdiffusion occurs due to defects on the motion path.

One common method to detect skyrmions in the lab is by Kerr microscopy. This is well suited for the detection of magnetic structures on the micrometer scale, but cannot be miniaturized down to the nanometer scale. To compete with established storage media methods, miniaturization of detection methods is essential. Magnetic tunnel junctions (MTJ) [4] are a promising tool to detect small magnetization changes. The selected Ta/CoFeB/MgO material system allows to build MTJs integrated into tracks in which skyrmions can be generated and moved along using current pulses. But this integration of MTJs into skyrmion racetracks remains challenging, even though they work fine independently.

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Topological Hybrids of Magnons and Magnon Bound Pairs

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Topological phases of electrons promise novel spintronic applications. Surprisingly, even magnetic insulators with a trivial electronic spectrum can feature topological quasiparticles in the form of magnons. The resulting chiral edge magnons may serve as unidirectional information channels of magnetic signals that are free of Ohmic heating. So far, magnon topology was discussed within a semiclassical approximation and quantum effects have been neglected.
Herein [1], we show that ferromagnets can host novel topological spin excitations when accounting for the "quantumness" of the spin degree of freedom. Explicitly, we show that single magnons hybridize with magnon bound pairs in fully saturated spin-anisotropic quantum magnets without spin conservation. The resulting chiral edge excitations are exotic composites that carry mixed spin-multipolar character, inheriting spin-dipolar and spin-quadrupolar character from their single-particleness and two-particleness, respectively. In contrast to established topological magnons, the topological effects discussed here are of genuine quantum mechanical origin and vanish in the classical limit. Our results hold important implications for the intrinsic anomalous thermal Hall effect in magnetic insulators.

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Magnetic skyrmion season II

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Though the magnetic skyrmion has drawn a lot of attention as a topologically protected spin texture for the use of magnetic information carrier, lot of people has been skeptical for its use in spintronic device. One of the reasons for this is that its generation has been possible by the local perturbation of its spin texture. If one can generate this magnetic skyrmion at the position aimed by systematic manipulation, it will be the good starting point for the preparation of skyrmionic device. We have shown several methods to generate this magnetic skyrmion by the systematic approach, so that this general method can be easily adopted by other groups. In this very short talk, we will present several devices like magnetic skyrmion racetrack memory, skyrmion transistor and neuromorphic application.

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Tuning all-optical magnetization switching efficiency by laser pulse wavelength variation

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The relevance of heat-assisted magnetic recording (HAMR) motivates ongoing research and development in magnetization manipulation. We study all-optical helicity-dependent switching (AOHDS) of FePt granular media as a viable alternative method for magnetic writing of HAMR media. The interplay of magnetic dichroism and inverse Faraday effect is currently understood as driving process behind the magnetization reversal. Ab-initio calculations of magnetic dichroism and inverse Faraday effect for the switching rates of single FePt nano particles provided us with a stochastic model for the switching process[1]. We now present data for the wavelength dependent efficiency of the writing process from 800 nm - 1550 nm. We greatly acknowledge the DFG funding within the project "Fundamental aspects of all-optical single pulse switching in nanometer-sized magnetic storage media.

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Surface magnetization of Cr_2O_3 (104) quantified via scanning NV magnetometry

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Magneto-electric antiferromagnets are candidate materials for future spintronic devices. While antiferromagnets offer high speed, low power consumption and robustness to external fields, magneto-electrics allow manipulation of the magnetic order parameter not only via magnetic signals, but also via electric signals [1, 2]. Readout and manipulation of the antiferromagnetic order on the nanoscale typically relies on local probes sensitive to the surface magnetization. Therefore, its optimization is key challenge in device engineering. Here we investigate the surface magnetization of an oblique cut of single crystal Cr_2O_3 using scanning probe nitrogen-vacancy center magnetometry. The (104) surface normal is at an angle of 38.5° to the uniaxial anisotropy axis of Cr_2O_3. By magneto-electric annealing [3], a homogeneous antiferromagnetic order is initialized. We then measure the stray magnetic fields produced by topographic steps fabricated by ICP etching. The steps have various angles with respect to the c-axis in-surface component, allowing us to probe different `cuts` of the magnetization. We finally consider a simple model based on a homogenous surface magnetization strength and orientation for the various crystal facets. We find good agreement between this model and the recorded stray fields for a magnetization aligned with the bulk c-axis orientation. The predicted magnitude agrees with previous results of measurements on (001) surfaces [4]. We hope that these findings may aid in understanding the relation between surface and bulk magnetic order in antiferromagnets and aid in the development of antiferromagnetic spintronic devices.

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Stability and Nucleation of Magnetic Skyrmions in the 2D van der Waals Magnets Fe_3GeTe_2

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Recently, the combination of 2-dimensional (2D) magnetism with the field of spintronics, i.e. the manipulation of magnetic states with electric currents, has started to gain much traction in modern solid-state physics. The prospect of highly efficient low-dimensional devices, extreme ease to fabricate versatile heterostructures by stacking of separate individual layers, and the report of chiral topological magnetic solitons in 2D itinerant ferromagnets have further enhanced the field's interest in this fascinating class of materials. Requirements for technological implementation, however, are generally to realize both the fabrication of nanoscale devices and to understand different potential ways to tailor the material parameters and ferromagnetic ordering temperatures in desirable ways.

In this work, we utilize real-space imaging of the magnetic texture in thin flakes of the van der Waals magnets Fe_3GeTe_2 to determine magnetic phase diagrams of various exfoliated films with varying compositions. We furthermore realize devices for local injection of skyrmions by means of vertical nanocontacts. Our findings show that changes in the composition significantly alter the magnetic behavior and may be used to tune the stability of skyrmions or other magnetic textures in these novel magnetic systems. Ultimately, the choice of composition and nucleation mechanism result in a selective stabilization of a variety of (meta-) stable magnetic configurations. Especially individual skyrmions can then be injected by targeted current pulses through a nanocontact. Our findings open novel perspectives for designing van der Waal heterostructure-based devices incorporating topological spin textures.

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Flexomagnetism and vertically graded Néel temperature of antiferromagnetic Cr_2O_3 thin films

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Thin films of antiferromagnetic insulators (Cr_2O_3, NiO etc.) are a prospective material platform for magnonics, spin superfluidity, THz spintronics, and non-volatile data storage. A standard micromagnetic approach for the description of such thin films relies on the effective parameters being homogeneously distributed along the film thickness. The family of magnetomechanical effects includes piezo- and flexomagnetic responses, which determine the modification of the magnetic order parameters due to homogeneous or inhomogeneous strain, respectively. Accounting for the magnetomechanical coupling promises technological advantages: the cross-coupling between elastic, magnetic and electric subsystems opens additional degrees of freedom in the control of the respective order parameters [1, 2, 3].
In this work, we discover the presence of flexomagnetic effects in epitaxial Cr_2O_3[4]. We demonstrate that a gradient of mechanical strain affect the order-disorder magnetic phase transition resulting in the distribution of the Neel temperature along the thickness of a Cr_2O_3 film. The inhomogeneous reduction of the antiferromagnetic order parameter induces a flexomagnetic coefficient of about 15 μB nm^{-2}. The antiferromagnetic ordering in the strained films can persist up to 100°C, rendering Cr_2O_3 as a prospective material for industrial electronics applications. Strain gradient in Cr_2O_3 thin films enables fundamental research on magnetomechanics and thermodynamics of antiferromagnetic solitons, spin waves and artificial spin ice systems in magnetic materials with continuously graded parameters.

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Time-resolved scanning NV magnetometry of dynamic domain walls

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Understanding the micromagnetics of current-induced motion of domain walls (DW) in thin magnetic films is crucial for the development of novel spintronic devices. While techniques such as electrical transport measurements and MOKE imaging are well-established in this field, they only provide a macroscopic picture. In contrast, scanning diamond magnetometry has proven itself a suitable platform for nanoscale imaging of the internal DW structure [1, 2, 3], benefiting from its compact table-top setup under ambient conditions compared to more demanding microscopic techniques, such as X-ray and electron scattering. Here, the local magnetic stray field is measured by optically detecting magnetic resonances of a single nitrogen-vacancy (NV) defect in diamond [4]. However, it is inherently not a single-shot method [4] which is why scanning NV magnetometry has so far been restricted to imaging static structures.

The goal of this project is to overcome this limitation and enable time-resolved NV magnetometry, which would be an important step towards imaging dynamic DWs. At the initial stages of the project, we aim for a system with a high repeatability of the DW motion to lay the groundwork for applying stroboscopic pump-probe techniques. Here, we focus on reproducible injection and geometrical confinement of DWs in ferromagnetic Co/Pt and ferrimagnetic GdCo/Pt multilayers. Both systems exhibit perpendicular magnetic anisotropy and strong interfacial Dzyaloshinskii-Moriya interactions that stabilize chiral DWs, which can be moved via current-induced spin-orbit torque. Afterwards we will proceed towards pump-probe measurements by driving the DWs with AC currents and synchronizing the stray field readout with the DW's motion, thereby paving the way for time-resolved scanning NV magnetometry.

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Spin-current driven Dzyaloshinskii-Moriya interaction in the multiferroic $BiFeO_3$ from first-principles

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The electrical control of magnons opens up new ways to transport and process information for logic devices. In magnetoelectrical multiferroics, the Dzyaloshinskii-Moriya (DM) interaction directly allow for such a control and, hence, is of major importance [1]. We determine the origin and strength of the (converse) spin current DM interaction [2,3] in the *R3c* bulk phase of the multiferroic $BiFeO_3$ based on density functional theory. Our data supports only the existence of one DM interaction contribution originating from the spin current model. By exploring the magnon dispersion in the full Brillouin Zone, we show that the exchange is isotropic, but the DM interaction and anisotropy prefer any propagation and magnetization direction within the full (111) plane. Our work [4] emphasizes the significance of the asymmetric potential induced by the spin current over the structural asymmetry induced by the anionic octahedron in multiferroics such as $BiFeO_3$.

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Chiral Induced Spin Selectivity effect at molecules metal hybrid interfaces

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With the discovery of the chiral-induced spin selectivity effect (CISS) effect indicates that chiral organic molecules can act as spin filters [1]. The results show that the process of an electron passing through a chiral molecule has obtained a high spin polarization [2]. Therefore, exploring the spintronic phenomena at magnetic molecule/metal interfaces probing the CISS effect via the inverse spin Hall effect in hybrid devices is our focus of interest. For this, we will inject a pure spin current from a magnetic insulator at ferromagnetic resonance into the hybrid spin detection layer via spin pumping and measure the resulting inverse spin Hall effect voltage. Quantifying the change in spin Hall angle due to the adsorption of molecules will explain the CISS effect at the hybrid interface.

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Angle-resolved photoemission study of transition metal phosphorus trisulfides in the 2D limit

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In the past decade, the interest in two-dimensional materials has increased in various communities due to their novel mechanical, electrical and optical properties in the transition to just a few atomic layers. While some 2D materials like graphene and transition metal (TM) dichalcogenides (TMDs) have already a widespread use in applications across various fields, a new class of components has arisen in the past years: the transition metal chalcogenophosphates ($TMPX_3$).

Especially the group of $TMPS_3$, where the transition metal is surrounded by phosphor and sulfide atoms, provides the perfect opportunity to study magnetic effects in the 2D limit. In the case of TM=Fe, Mn, Ni, it is possible to study different types of antiferromagnetic ordering with Néel-temperatures in the range of 82 to 158 K [1]. With the recent interest in antiferromagnetic systems for spintronic applications, which is routed in their insensitivity to external magnetic fields and their ultrafast dynamics in the terahertz frequency range [2], this group of materials opens a platform to study effects that could impact the further development of devices for antiferromagnetic spintronics [3].

In my contribution I will present a series of ARPES measurements on $MnPS_3$, $NiPS_3$, and $FePS_3$ crystals. Thereby, I will show recent band structure measurements of all three materials on thick layers (>100ML) and in the case of FePS3 an additional comparison with μ-ARPES measurements on flakes in the monolayer regime. Additionally, first insights into the arrangement of organic molecules (in this case pentacene) have been gained by evaporating a monolayer coverage on top of the bare surface. This includes the energy-level alignment of various molecular orbitals, investigated with the help of photoemission orbital tomography.

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Recent trends in magnetic sensor demands

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Magnetoresistive sensors penetrate more and more the market of magnetic sensors. This is mainly driven by the advantages of spintronic TMR sensors (tunnelmagnetoresistive sensors). Their main advantage is high signal output combined with low temperature drift. In addition, TMR sensors can be designed with a high degree of flexibility to fit different application like switches, angle or field sensing. Field sensing with excellent linearity over wide field range is a key property for high accuracy current sensors.

In my talk I would like to explain some future requirements in our market. New spintronic principles should be benchmarked against the existing MR technologies. Higher accuracy, less power consumption or lower noise are properties which are very demanded. Under no circumstances the reliability of the device can be ignored. Long time stability is an absolute must for all industrial or automotive applications especially stability at high temperatures (150°C or higher) and high magnetic fields (up to 500mT). But also the sensitivity in different field directions becomes more and more challenged.

References

Spinel FeV_2O_4: A new opportunity in spintronics

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Spinel iron vanadate, FeV_2O_4 (FVO), is a strongly correlated insulating oxide which displays several functionalities such as, low-temperature ferrimagnetism [1], ferroelectricity [2] and multiferroism [3]. FVO adopts different crystal structures with varying temperatures, which are associated to different orbital orderings owing to both Jahn-Teller active Fe^{2+} and V^{3+} ions [4]. Some of the authors have already demonstrated the possibility to grow epitaxial FVO films by using a pulsed laser deposition technique with a Ar-based partial pressure [5][6]. The large compressive strain onto $SrTiO_3$ (STO) single crystals, allowing a perpendicular magnetic anisotropy of the FVO thin films, make them potential candidates for spintronics studies.

We have grown Pt/FVO//STO heterostructures to engineer Hall bar shaped devices via a combination of optical lithography and Ar-ion milling processes. The temperature dependence of the observed Spin Magnetoresistance (SMR) amplitude mostly follows the FVO ferri-magnetic properties with onset around 140 K. Also, second-armonic measurements confirmed a spin-orbit torque induced modulation of the FVO magnetization. Finally, and more importantly, in some of our devices we found not only a relatively large SMR value (> 1%), but also a large SMR anisotropy depending upon the orientation of the external magnetic field, i.e. 0º or 180º with respect to the sample normal. This unusual behaviour, and reported in Figure 1, might be linked to the presence of a non-zero spin-orbit coupling in FVO thin films which endow the sytem with a peculiar chiral funtionality, still to be understood.

We believe that the observed large SMR signal in our Pt/FVO//STO heterostructures, although to be fully understood, will open the door to spinel iron vanadates as promising material platform for the next-generation oxide-based spintronics.

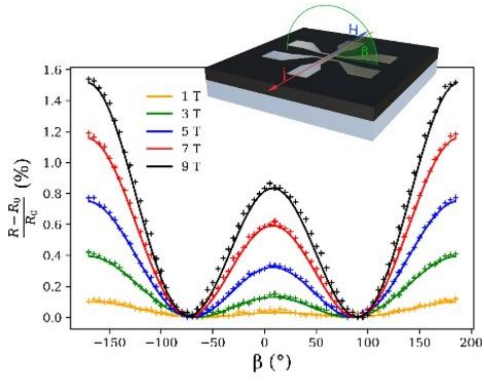

Figure 1 Anisotropy of the SMR signals acquried at different H and 60 K.

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Berryology and Anomalous Hall effect in compensated ferrimagnet

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It has been long believed that the anomalous Hall effect (AHE), discovered in 19th century, accompanies nonvanishing magnetization. The modern interpretation has been available only early of this century invoking topology or Berry curvature [1]. Recently, however, some antiferromagnets exhibit AHE even with vanishing magnetization [2]. Here, the study is extended to compensated ferrimagnet, Mn_3Al, a Heusler compound. Indeed, Berry curvature and local magnetization or locally broken play important role. To do so, group theoretical approach is adapted for analysis more specifically magnetic space group approach [3]. We found two regions characteristically different in terms of degeneracy are essential for nonvanishing AHE.

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Enantiospecific adsorption on a ferromagnetic surface at the single-molecule scale

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In recent years, chirality-induced spin selectivity (CISS), an effect arising from electron spin interplay with the handedness of chiral molecules [1,2], has gained significant interest as a potential application in spintronics and enantioselective chemistry and is predicted to lead to a chirality-based quantum leap in quantum sciences [3]. Using a low-temperature spin-polarized scanning tunneling microscope, we investigated the deposition characteristics of chiral heptahelicene molecules on two monolayers of Fe on W(110), Co bilayer nano-islands on Cu(111) and for comparison on Cu(111).We find that the sublimed molecules remain intact and adsorb with helical axis aligned parallel to the surface, allowing determination of the handedness of each molecule from topographic STM images. Three degenerate in-plane orientations on Cu(111) and Co(111), reflecting substrate symmetry, and only two on Fe(110), i.e., fewer than symmetry permits, indicate a specific adsorption site for each substrate [4]. As a consequence of these results, we have been able to investigate the enantiospecific adsorption of heptahelicene molecules on ferromagnetic Co bilayer nanoislands at the single-molecule scale [5]. High-resolution and spin-polarized STM images enable direct determination of the enantiomeric adsorption ratio R on oppositely magnetized Co nanoislands. Statistical analysis of more than 700 molecules on 110 islands yields $R = 0.69 \pm 0.05$. The well-defined structural, electronic, and magnetic properties of the molecule-substrate systems make our results readily amenable to theoretical analysis and modeling that will hopefully shed light on the microscopic origin of enantiospecific adsorption on ferromagnetic surfaces.

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Readout of single molecule magnets with semiconductor spin qubits

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Magnetic nanostructures such as single molecule magnets (SMMs) provide a great potential for the implementation of quantum digits (qudits) [1,2]. Here magnetic ion centers embedded in organic ligand matrices are used. For readout the SMMs are coupled to an electron on a quantum dot formed in a two-dimensional quantum well inside the semiconductor placed in a home-built dilution cryostat. Special chip designs of the semiconductor heterostructure (GaAs, SiGe, MOS) are needed to increase the coupling to the SMMs. The readout of the electronic spin on the quantum dot in the semiconductor heterostructure can be carried out by a single electron transistor (SET) through spin to charge conversion. In summary, this project strives to implement the manipulation and readout of SMMs using newly developed gate-defined semiconductor quantum dots.

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Approaching machine learning with nonlinear magnonic hardware

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Combining spin waves and spin textures for neuromorphic computing seems like a wonderful thing to do. Numerous publications in the last couple of years demonstrated possible schemes for unconventional computing. The success is based on the nonlinearity of spin waves and the incredible density and robustness of spin textures. Bringing both together, nonlinear spin waves in spin textures, is not just a simple advancement of magnonics, but is also surprises with some unexpected phenomena.

We demonstrate recognition of pattern sequences in a seriell data stream in the microwave frequency range using nonlinear spin waves in a single magnetic vortex [1]. The approach of multiplexing in the frequency domain in a quantized system with delocalized spin waves circumvents the standard problems of magnonics such as high spatial decay and limited lifetime. Especially for brain-inspired schemes, which rely on many connections between nonlinear nodes, the transitions between different spin-wave eigenmodes by stimulated magnon-magnon scattering [2] is unexplored territory.

The effective number of nonlinear nodes can be extended by generating spin-wave frequency combs [3] which spontaneously appear in magnetic vortices by the mutual interaction of the vortex core gyration and the spin-wave eigenmodes [4].

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Experimental investigation of mesoscale Dzyaloshinskii-Moriya interaction

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Low-dimensional ultra thin magnetic systems represent the best scientific platform for the investigation of structural inversion symmetry breaking effects [1,2]. Namely, thin magnetic layer being in contact with non-magnetic material with large spin-orbit coupling obtains the intrinsic Dzyaloshinskii-Moriya interaction (iDMI) [3,4,5], that is responsible for the formation of chiral non-trivial magnetic textures, e.g. skyrmions and chiral domain walls. These textures being topologically stable with particle-like properties introduce great potential for their application in novel logic and memory devices [4,6]. The iDMI optimization is possible only by adjusting structural and interface properties of the layer stack. A viable alternative to a structural screening is the break of local inversion symmetry appearing in curvilinear structures of conventional materials, which introduces extrinsic DMI [7]. Here, we provide the first experimental study of the mesoscale DMI (mDMI), the symmetry and strength of which are determined by the geometric and material parameters of the magnetic system [8]. To demosntrate this we fabricated spatially corrugated ultra thin asymmetric magnetic layers and compared the resulting magnetometry and transport responses with the reference rectilinear samples.

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Imaging the antiferromagnetic domain structure of hematite and its magnetic field dependence

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In recent years, antiferromagnets have gained increasing attention for spintronics applications due to their favorable properties such as vanishing stray fields. Moreover, the magnetic domain formation mechanism is different from ferromagnets. Therefore, we present here new results on the canted antiferromagnet hematite (α-Fe_2O_3). The canting of the orientation of spins leads to a small, magnetic moment.
Additionally, in-plane magnetized domains were found. Applying an in-plane magnetic field leads to an increase of the size of parallelly aligned domains. In turn, this leads to movement of the domain walls, depending on the magnetic field strength.
To study this, we have imaged the domain structure of α-Fe2O3 by taking x-ray magnetic linear dichroism (XMLD) contrast images of the domain structure of α-Fe_2O_3 by total electron yield using a scanning x-ray microscope (see Fig. 1). In TEY, the surface is contacted electrically and the voltage to counteract the surface charge created by the removed electrons is measured. This is applicable within an applied magnetic field and allows to study the domain structure, as well as the domain wall movement, depending on the magnetic field (Fig. 1).

Careful evaluation of these dependences can provide insights into the origins of the domain structure observed in hematite.

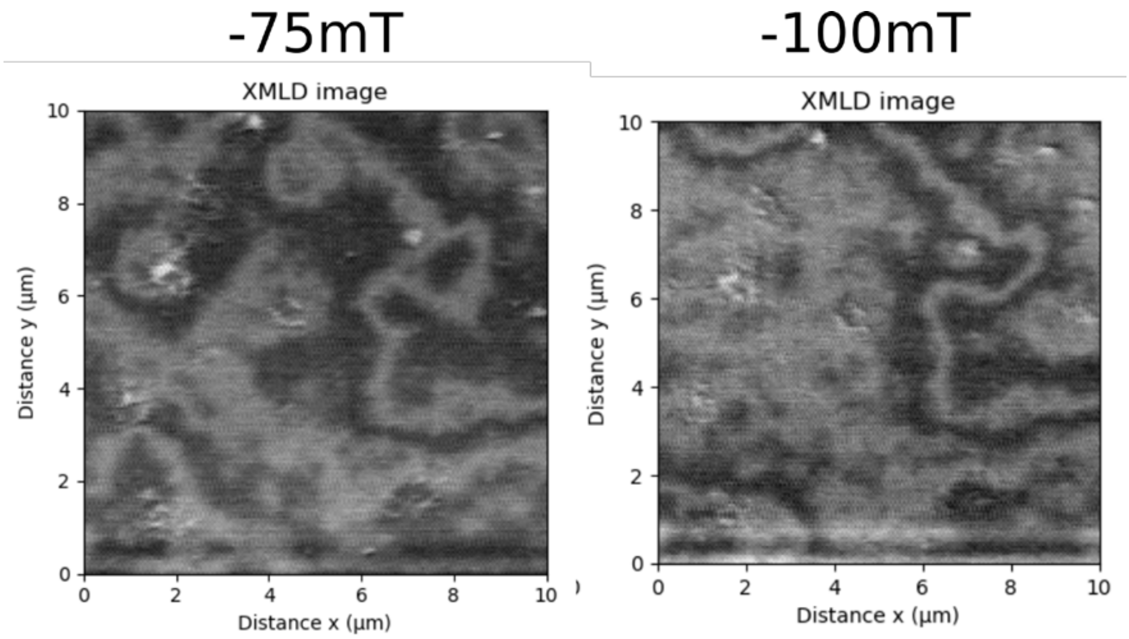

Figure 1 XMLD contrast of STXM images showing the magnetic domain structure of hematite for two different externally applied in-plane magnetic fields. A clear change is visible, where the size of light grey colored domains increases, while the dark grey domains shrink. Evaluating the movement of domain walls can prove useful for a better understanding of the origin of domain formation.

Magnon-optic effects with spin-wave leaky modes in Gires-Tournois interferometer

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Wood's anomaly (WA) is a phenomenon manifesting as a decrease of the reflected waves amplitude due to the excitation of a surface mode [1] that is still being investigated in photonics [2]. Another intriguing effect observed in the reflection of obliquely incident waves is a spatial shift of the reflected waves known as the Goos-Hänchen effect (GHE) [3,4]. We propose a magnonic realization of the Gires-Tournois interferometer (GTI) [5,6] by placing a stripe above the edge of a magnetic layer. This system is a suitable platform to observe counterparts of both WA and GHE for spin waves (SW). We use micromagnetic simulations to study the reflection of an oblique incident SW beam at GTI. We found the resonance conditions required to efficiently excite SW modes in the GTI by the incident SW beam. This gives rise to magnonic WA in our system as excited mode carries away part of the incident beam energy. The excited modes are confined in GTI and remit SWs partially back to the system; therefore, we classify them as 'leaky-modes'. The consequence of the leaky-mode is the creation of multiple spatially shifted SW beams in the layer parallel to one another. Furthermore, the excitation of the leaky-modes is accompanied by a significant GHE for the primary reflected beam up to 3 wavelengths and shift up to 15 wavelengths for the secondary reflected beam. Our results extend the understanding of SW-interferometer interactions and the creation of localized SW leaky-modes.

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Development of ultrafast soft X-ray magnetic holography at SwissFEL

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X-ray imaging techniques enabled a significant advancement in the understanding of the physics driving magnetic systems, thanks to the possibility of combining element selectivity, sensitivity to the magnetic and antiferromagnetic ordering through such contrast mechanisms as X-ray magnetic circular (XMCD) and linear (XMLD) dichroism, and high spatial and temporal resolutions. Up to now, most of the X-ray imaging research on spintronics has been performed on the synchrotron-based microscopes. However, the constant push towards the investigation of faster processes occurring at smaller length scales is now encouraging the implementation of time-resolved X-ray imaging techniques at X-ray free-electron lasers.

Here, we present an ongoing project devoted to the development of time-resolved magnetic imaging at the ultrafast timescales at Maloja endstation of Athos beamline at SwissFEL (PSI, Switzerland). The setup will be based on X-ray holography [1], which is a lensless coherent diffractive imaging technique where the interference pattern between the X-ray beam crossing the sample and a set of defined references is recorded on a 2D detector. The sample image is then recovered via Fourier transform of the recorded interference pattern. Since X-ray holography is an intrinsically drift free and a full-field microscopy technique, it is particularly well suited for free-electron lasers, where shot-to-shot variations render scanning microscopy techniques unsuitable [2, 3].

The recently commissioned Athos beamline at SwissFEL, with its 16 Apple-X undulators, is currently the only soft X-ray free electron laser source (250 to 1800 eV, covering all of the relevant edges of the magnetic elements) with a fully controllable X-ray polarisation, which is essential for both XMCD and XMLD contrast mechanisms. Moreover, both electrical and optical excitation schemes will be available for the time-resolved pump-probe experiments. First beam on the holography endstation is expected in February 2023.

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Optically induced spin dynamics in exchange-coupled spin models

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Magnetization switching dynamics in multi-sublattice ferrimagnets with itinerant electronic states after instantaneous excitation is studied in a microscopic approach to an exchange-coupled two-sublattice model with itinerant and localized (flat-band) electrons. The interacting equilibrium state is determined at the mean-field level and the electronic dynamics due to the exchange interaction between the sublattices are described at the level of scattering integrals [1]. Different dynamical scenarios in this model are discussed. Preliminary results are presented on ab-initio calculations of the electronic structure of molecular magnets on surfaces, which serve as the basis of effective spin-models to describe their optically induced dynamics.

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In-situ correlation of electrical (magneto-)transport effects with magnetic textures in a transmission electron microscope

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Spintronics naturally relates magnetic phenomena to transport properties. For example, magnetometry measurements are used as an input parameter to explain the anomalous Hall effect. Recently, magnetic textures such as Skyrmions were related to intriguing transport observations such as the topological Hall effect. However, the stability of magnetic textures depends on the sample geometry, therefore, a correlation of magneto-transport and transmission electron microscopy (TEM) data is challenging, if not conducted on identical samples.
To overcome this, we devised a measurement platform that allows for the conduction of magneto-transport measurements while simultaneously performing Lorentz-TEM (L-TEM) investigations. A special holder is used to measure transport data. Hall bar structures are prepared using conventional lithography on thin film samples or TEM lamellae cut from single crystals placed on a measurement chip with a Si_xN window.
In Lorentz mode, the objective lens of the microscope applied a magnetic field perpendicular to the sample plane. Acquisition of L-TEM images and the Hall voltage as function of the magnetic field were conducted automatically. Our setup allows us to follow the field dependence of the Hall voltage while simultaneously monitoring the magnetic texture.
First, we will present thin film Nickel samples demonstrating the general functionality of the setup. Then, we will present our experiments of the Heusler compound $Mn_{1.4}PtSn$: On the one hand, this material is known to host interesting magnetic textures such as a helical phase, non-topological bubbles and anti-Skyrmions. On the other hand, spintronic transport experiments in this material class already revealed fascinating features in the Hall signal attributed to the topological Hall effect. Our setup allows for the direct correlation of the Hall effect with the magnetic field dependent occurrence of both non-topological (NT) and topologically protected magnetic phases.

Electric control of magnon phase and magnonic Aharonov-Casher effect

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Control of transport characteristics of magnons employing electric fields is an fascinating and important direction of modern magnonics. Exploring new effects associated with the influence of electric fields on magnons is promising for novel magnonic applications requiring effective manipulation of the phase of magnon currents.
In this work, the effect of a strong electric field on the phase of spin waves propagating in ferromagnetic films of yttrium iron garnet (YIG) was studied. The electric field was applied perpendicular to the film plane along the crystallographic axis <111>. The experiment was carried out in different spin-wave propagation geometries when backward volume magnetostatic spin waves (BVMSW) and magnetostatic surface spin waves (MSSW) were excited. Using a vector network analyzer, the spin-wave phase shift, sensitive to various external influences, was accurately measured on the propagation path.
First, by observing the electrically-induced phase shifts of BVMSWs, we determined the contribution of linear and quadratic magnetoelectric effects for the used YIG film. Further, the obtained magnetoelectric coefficients were used to approximate the phase shifts of MSSWs. It turned out that the MSSW phase shift significantly exceeds the phase shift of the bulk wave. Hence, such an approximation is possible only with the inclusion of an additional phase shift, which depends linearly on the spin-wave wavenumber, the propagation length, and the electric field strength. This shift reaches a value of 1.2°, which is comparable to the shift caused by magnetoelectric effects. We interpret this additional phase shift as the contribution of the magnon Aharonov-Casher effect, which is a geometric accumulation of the magnon phase as it passes through the electric field region.
This research was funded by the ERC within the Advanced Grant No. 694709 “SuperMagnonics” and by the DFG within the Transregional Collaborative Research Center – TRR 173/2 – 268565370 “Spin+X” (project B04). The authors are grateful to Roman Verba, Victor S. L’vov, and Mathias Weiler for fruitful discussions.

Defect nanostructure and its impact on magnetism of α-Cr_2O_3 thin films

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Thin films of the magnetoelectric insulator α-Cr_2O_3 are technologically relevant for energy-efficient magnetic memory devices controlled by electric fields [1-3]. In contrast to single crystals, the quality of thin Cr_2O_3 films is usually compromised by the presence of point defects and their agglomerations at grain boundaries, putting into question their application potential. We experimentally investigated the defect nanostructure of magneton-sputtered 250-nm-thick Cr_2O_3 thin films prepared under different conditions on single crystals of Al_2O_3 (0001) and correlate it with the integral and local magnetic properties of the samples [4]. We evaluated the type and relative concentration of defects. For this purpose, positron annihilation spectroscopy (PAS) was used as a unique probe for open-volume defects in thin films. The results obtained for the thin-film samples are compared to single crystal data. Our analysis reveals that the Cr_2O_3 thin films are characterized by the presence of complex defects at grain boundaries, formed by groups of monovacancies, coexisting with monovacancies and dislocations. The concentration of complex defects can be controlled by the sample fabrication conditions. The defect nanostructure strongly affects the magnitude of the electrical readout, which is measured of the Cr_2O_3 samples capped with a thin layer of Pt relying on spin Hall effect [5]. Furthermore, the presence of larger defects like grain boundaries has a strong influence on the pinning of magnetic domain walls in thin films. Independent of these findings, we showed that the Néel temperature, which is one of the important technological metrics, is hardly affected by the formed defects in a broad range of deposition parameters.

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Kerr microscopy for all-optical helicity-dependent magnetization switching (AOHDS)

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The demand of data storage capabilities is growing rapidly since the invention of the computer. The development of big data in science and economy intensifies this evolution.
To fulfill the demand of storage capabilities there is need of new data storage techniques. One of these new techniques is heat assisted magneto recording (HAMR) where the bit size is drastically decreased by high coercive fields of granular FePt.
Besides the heat assisted writing with a magnet, we are investigating the writing on HAMR media with all-optical helicity-dependent switching (AOHDS) as a novel data storage technology [1]. Wide field Kerr-microscopy is a well-suited method to explore and analyze the outcome of our AOHDS experiments.
We present a build from scratch and cost-efficient Kerr microscope for the observation of magnetic domains and writing with AOHDS on HAMR media simultaneously.
It can also be used for the investigation of skyrmions and can be refined to investigate magnetization changed in a pump-probe experiment after the deposition of ultrashort laser pulses on magnetic thin films.

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Ultrafast response of induced and intrinsic magnetic moments in 3d/5d material systems

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The ultrafast and element-specific response of magnetic systems containing ferromagnetic 3d transition metals and 4d/5d heavy metals is of interest from both a fundamental as well as an applied research perspective. However, to date no consensus about the main microscopic processes describing the interplay between intrinsic 3d and induced 4d/5d magnetic moments upon femtosecond laser excitation exist. In this work, we study the ultrafast response of CoFeB/Pt bilayers with resonant, core-hole spectroscopy in the extreme ultraviolet spectral range using high harmonic radiation. We show that the combination of magnetic scattering simulations and analysis of the energy- and time dependent magnetic asymmetries allows to accurately disentangle the element-specific response in spite of overlapping Co and Fe $M_{2,3}$ as well as Pt $O_{2,3}$ and N_7 resonances. We find a considerably smaller demagnetization time constant as well as much larger demagnetization amplitudes of the induced moment of Pt compared to the intrinsic moment of CoFeB. Our results are in agreement with enhanced spin-flip probabilities due to the higher spin-orbit coupling localized at the heavy metal Pt compared to Fe and Co, as well as with the recently formulated hypothesis of a strong sensitivity to the average spin orientation between intrinsic and induced magnetic moments following a laser generated incoherent magnon population.

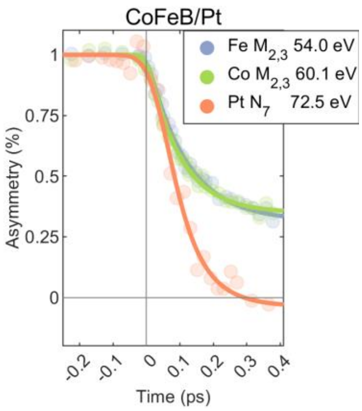

Fig. 1: Normalized magnetic asymmetry as a function of time delay for Fe (54.0 eV), Co (60.1 eV) and Pt (72.5 eV). We observe a significant faster and more pronounced loss of the induced magnetization compared to the intrinsic moment of Co and Fe.

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Exchange Enhancement of Ferromagnetic Resonance Frequencies in $Mn_2Au/Ni_{80}Fe_{20}$

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In the future, antiferromagnets (AFMs) as active components will bring favorable advantages to spintronics: Robustness to external magnetic fields, temperature stability of the Néel ordered state and lack of stray fields. Therefore, AFMs are suitable for ultrafast and ultra high density spintronics. Strong exchange coupling between Mn_2Au and thin layers of Permalloy ($Ni_{80}Fe_{20}$) has been shown [1]. As a consequence, the coercive field of $Mn_2Au/Ni_{80}Fe_{20}$ was reported to be 0.5 T, which is high compared to 0.02 T in CuMnAs/Fe [1]. Due to strong exchange coupling, the AFM Néel vector and the ferromagnetic (FM) magnetization rotate coherently, when an external field is applied to the FM. Control of the Néel ordered state in Mn_2Au and the $Ni_{80}Fe_{20}$ spin dynamics has been studied by varying the $Ni_{80}Fe_{20}$ layer thickness [2]. Ferromagnetic resonance spectroscopy revealed two distinct frequencies for the coupled bilayer system, both of which lie above the resonance frequency of Permalloy [2]. We calculate the spectra of the magnons in the coupled FM/AFM system within micromagnetic model (Fig. 1(a)). Our model enables us to demonstrate how the interfacial exchange coupling enables tuning of the ferromagnetic resonance frequency by variation of the thickness of the ferromagnetic layer (Fig. 1(b)). We estimate the exchange coupling strength to be 2 T [2].

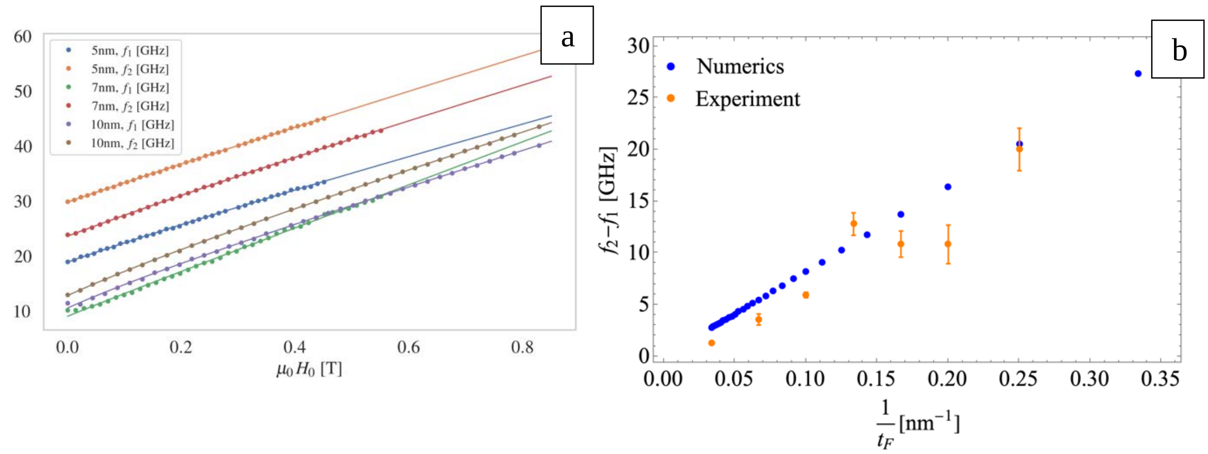

Figure 1: (a): Fitting of the Kittel formula to the FM resonance frequency data for varying $Ni_{80}Fe_{20}$ layer thicknesses. (b): Experimental [2] and numerical model data for the FM resonance frequencies as a function of the $Ni_{80}Fe_{20}$ layer thicknesses.

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Flexible and printed magnetic field sensors

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Work with spintronic functional elements for flexible magnetic field sensors, we was interested in improving their performance, relying on new materials and metrological approaches. We employ novel fabrication technics as an alternating magnetic field activation of self-healing of percolation network [1]. It allows to fabricate printable magnetoresistive sensors revealing an enhancement in sensitivity of more than one and two orders of magnitude, relative to previous reports. Printed electronics are attractive due to their low-cost and large-area processing features, which have been successfully extended to magnetoresistive sensors and devices [2]. This technology was enabled initially, by thin films magnetic field sensors, embedded in a soft and flexible format to constitute magntosensitive electronic skin (e-skins). But now we demonstrate what interactive electronics, based on flexible spin valve switches [3] or printed and stretchable Giant Magnetoresistive Sensors, could act also as a logic elements, namely momentary and permanent (latching) switches. All this printing technology aspects are yet to be developed to comply with requirements to mechanical conformability of on-skin appliances. Due to the fact that the metallic layer is subjected to unsteady mechanical stresses, deposition of the magnetic sensor onto few microns thick non-rigid substrate creates a numerous problems, and the strain sensitivity is the first effect which have to be discussed. The thermoelectric effect is the second effect that also have to be considered in order to minimize thermal errors. These aspects will be discussed more detailed in this contribution.

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