Book of Abstracts

ICMFS2024

Welcome to the 25th International Colloquium on Magnetic Films and Surfaces (ICMFS2024), which will be held from July 7 to 12, 2024 in Perugia, Italy.

The ICMFS2024 is a satellite conference to the 22nd International Conference on Magnetism to be held from June 30 to July 5 2024 in Bologna, Italy, just 237 km north of Perugia (www.icm2024.org). The ICMFS2024 continues the tradition of previous Colloquia, which started in 1964 in London, UK. This is the first time the Conference is held in Italy.

Pursuing the idea of free circulation of scientists, the ICMFS2024 will bring together scientists from all areas of magnetism in lower dimensions. The Colloquium aims at the exchange of new results and ideas for advancing the field of magnetism at surfaces, interfaces, in micro- and nanostructures as well as of spin-dependent phenomena.

The structure of the Colloquium will be a single session style. It will consist of invited and oral talks given by world leading experts from research institutes, universities and industry. There will be extensive poster sessions, where attendants and particularly early career scientists and students are encouraged to present their work related to the fields covered by the ICMFS2024.

Francesca.Casoli.and.Gianluca.Gubbiotti.(Chairs.of.ICMFS8680)

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Program in detail

Sunday 7 July	
16:00 - 17:30	**The opening ceremony will be at the Aula Magna of the University of Perugia** Shuttle buses will depart at 16:30 and 17:00 from the Hotel Giò to the Aula Magna of the University of Perugia. The same buses will return to the Hotel Giò after the Welcome Reception. ***Registration***
17:30 - 18:00	***Opening***
Chair	***Paola Tiberto***
18:00	*Plenary* ***Claire Donnelly*** - Max Planck Institute for Chemical Physics of Solids, Germany - "Mapping and controlling three dimensional spin textures"
19:00	*Plenary* ***Teruo Ono*** - Kyoto University, Japan - "Superconducting diode effect in superconductor/ferromagnet multilayers"
20:00	***Welcome Reception***

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Monday 8 July	
8:00 - 8:45	**Registration**
Chair	***Oksana Chubykalo-Fesenko***
08:45 - 09:15	**Tomas Jungwirth -** Institute of Physics, Czech Academy of Sciences, Czech Republic - "Altermagnets: An unconventional magnetic class"
09:15	**Anders Strømberg** - Norwegian University of Science and Technology, Norway - "On the antiferromagnetic-ferromagnetic phase transition in pinwheel artificial spin ice"
09:30	**Christina Vantaraki -** Uppsala University, Sweden - "Magnetic metamaterials produced by ion implantation"
09:45	**Haoran Chen** - Fudan University, China - "Nonrelativistic THz emission and antisymmetric planar Hall effect in RuO_2(101) films"
10:00	**Julio Antonio Larrea Jiménez** - University of São Paulo, Brasil - "Quantum materials under the effect of dimensionality and disorder"
10:15	**Sara Laureti** - ISM-CNR, Italy - "Co/Ni synthetic antiferromagnets heterostructures on polymer tapes: towards sustainable spintronics"
10:30 - 11:00	***C O F F E E B R E A K***
Chair	***Masaki Mizuguchi***
11:00 - 11:30	**Agustina Asenjo -** ICMM - CSIC, Spain - "Advanced Magnetic Imaging at the nanoscale "
11:30	**Filip Krizek** - Institute of Physics, ASCR, Czech Republic - "Atomically sharp domain walls in antiferromagnetic CuMnAs"
11:45	**Matthieu Bailleul**- CNRS - Université de Strasbourg, France - "Spin-polarized electron transport in single crystalline iron as function of temperature"
12:00	**Piotr Kuświk -** Institute of Molecular Physics Polish Academy of Sciences, Poland - "Tailoring magnetic anisotropy and domain wall chirality of Co/Ni bilayers by plasma oxidation"
12:15	**Sabine Pütter -** JCNS at MLZ, FZ Jülich, Germany - "Hydrogen absorption induced switching of the easy axis in Pt/Co/Pt"
12:30	**Milad Takhsha -** CNR - IMEM, Italy - "Spatially confined magnetic shape-memory Heuslers: implications for nanoscale devices"
12:45 - 14:15	***LUNCH BREAK***
14:15 - 15:45	**Poster Session - I**
Chair	***Cristiano Nisoli***
15:45 - 16:15	**Na Lei** - Beihang University, China - "Experimental demonstration of a skyrmion-enhanced strain-mediated physical reservoir computing system"
16:15	**Johanna Fischer** - SPINTEC, France - "Mechanisms governing weak Dzyaloshinskii-Moriya interaction in a heavy metal/ferromagnet/oxide system"
16:30	**Robert Frömter** - Johannes Gutenberg University Mainz Germany - "Homochiral antiferromagnetic merons, antimerons and bimerons realized in synthetic antiferromagnets"
16:45	**Vincent Cros** - Laboratoire Albert Fert, CNRS, France - "Three-dimensional skyrmionic cocoons in aperiodic magnetic multilayers"
17:00 - 17:30	***C O F F E E B R E A K***
17:30	**Amalio Fernandez-Pacheco** - Vienna University of Technology Austria - "Investigation of synthetic antiferromagnets with interlayer chiral interactions using X-ray magnetic techniques"
17:45	**Soma Miki** - Osaka University, Japan - "Hysteresis-free voltage creation/annihilation of magnetic skyrmions"
18:00	**Peter Fischer** - Lawrence Berkeley National Laboratory,USA - "Quantifying the topology of magnetic Skyrmions in three dimensions"
18:15	**Marisel Di Pietro Martinez** - Max Planck Institute for Chemical Physics of Solids, Germany - "Revealing the three-dimensional nature of the field-driven movement of magnetic topological defects"

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Tuesday 9 July	
9:00 - 12:45	**Perugia sightseeing**
12:45 - 14:15	***LUNCH BREAK***
Chair	***Silvia Tacchi***
14:15 - 15:00	**Sveva Avveduto** - CNR, Italy **-** "Women and science: an overview of data, open questions and possible solutions"
Chair	***Tomas Jungwirth***
15:00 - 15:30	**Volker Neu -** IFW Dresden, Germany - "Induced anisotropies and flux closure in self assembled, rolled magnetic membranes"
15:30	**Adam Cahaya** - Universitas Indonesia, Indonesia - "Rare-earth Spintronics: from orbital-momentum polarization to the Dzyaloshinskii-Moriya Spin density "
15:45	**Takayuki Hojo** - Tohoku University, Japan - "Magnetic anisotropy in half-metallic $Co_2FeAl_xSi_{1-x}$ Heusler alloy thin films"
16:00	**Hiroaki Sukegawa** - National Institute for Materials Science, Japan - "Exploring stack-structures for over 400% tunnel magnetoresistance in spin-valve-type CoFeB/MgO/CoFeB junctions"
16:15	**Robert Stamps -** University of Manitoba, Canada - "Bayesian inference using nanomagnet arrays"
16:30	**Mattia Benini** - CNR-ISMN, Italy - "Emergence of the Ferromagnetic-Glass Texture in Co layers hybridized with Molecules"
16:45	**Shinji Miwa** - The University of Tokyo, Japan - "Microscopic understanding of magnetoresistance in a chiral molecule-ferromagnet junction"
17:00 - 17:30	***COFFEE BREAK***
Chair	***Na Lei***
17:30 - 18:00	**Cristiano Nisoli** - Los Alamos National Laboratory, USA - "Vertex Frustration and Exotic Behaviors in Artificial Spin Ice"
18:00	**Dheerendra Bhandari** - Norwegian University of Science and Technology, Norway - "Clocking emergent magnetic monopole in square artificial spin ice"
18:15	**Todd Hastings** - University of Kentucky, USA - "Resonant soft x-ray studies of artificial spin ices containing defects of varying topological charge"
18:30	**Khalil Zakeri Lori** - Karlsruhe Institute of Technology, Germany - "Emergent spin–orbit induced phenomena in terahertz magnon dynamics in magnetic layered structures"

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Wednesday 10 July

Chair	***Agustina Asenjo***
08:45 - 09:15	**Masaki Mizuguchi** - Nagoya University, Japan - "Thermo-spin effects in nanostructured ferromagnetic thin films "
09:15	**Michael Tanksalvala -** National Institute of Standards and Technology (NIST), USA- "Element-specific FMR spectroscopy at high frequencies, detected with coherent extreme ultraviolet light"
09:30	**Alberto Pomar** - ICMAB - CSIC, Spain - "Tunning the antiferromagnetic phase in epitaxial thin films of $La_{1-x}Sr_xMnO_3$ prepared by polymer-assisted deposition"
09:45	**Ewa Madej** - Institute of Catalysis and Surface Chemistry Krakow, Poland - " Switching of Néel vector in hematite thin films by exchange coupling with cobalt layers"
10:00	**Oksana Koplak -** Università degli Studi di Milano Bicocca, Italy - "Structural and magnetic properties of patterned SmCo films"
10:15 - 11:00	***C O F F E E B R E A K***
Chair	***Satoshi Iihama***
11:00 - 11:30	**André Thiaville** - Université Paris-Saclay & CNRS,France - "Spin-orbit torque driven domain wall motion in the absence of Dzyaloshinskii-Moriya interactions"
11:30	**Jose Omar Ledesma Martin** - JGU- Mainz, Germany - "Investigating Orbital Hall Effect Materials for Efficient Magnetization Control"
11:45	**Benjamin Bony** - Laboratoire Albert Fert, France - "Orbital currents and torques on transition metals using interfacial orbital Rashba effect"
12:00	**Nicolas Sebe -** Laboratoire Albert Fert, France - "Large Interfacial Rashba Torques in Atomically Thin Co|Al Systems"
12:15	**Lucile Soumah** - SPINTEC, France - "Nanosecond scale stochastic magnetization reversals in perpendicular superparamagnetic tunnel junctions"
12:30	**Group photo**
12:45 - 14:15	***LUNCH BREAK***
14:15 - 15:45	**Poster Session - II**
Chair	***Marek Przybylski***
15:45 - 16:15	**Jian Shen** - Fudan University, Shanghai, China **-** "Oxide Materials for Spintronics"
16:15	**Eleftherios Niapos** - Brno University of Technology,Czech Republic - "Electrical control of exchange bias in HfO_2/CoO/Co heterostructures through voltage-driven oxygen ion motion "
16:30	**Gajanan Pradhan** - INRIM, Italy - "Electric field control of magnetization in FeGa microstructures on PMN-PT "
16:45	**Nina-Juliane Steinke** - Institut Laue-Langevin, France - "Magnetism of pure and Fe-doped multiferroic CoCr2O4 thin films"
17:00 - 17:30	***C O F F E E B R E A K***
Chair	***Robert Stamps***
17:30 - 18:00	**Gustav Bihlmayer** - Forschungszentrum Jülich, Germany - "Ab initio exploration of graphene intercalated lanthanides
18:00	**Tim Drevelow** - University of Kiel, Germany - "Complex non-collinear spin structure of a Mn double layer on Ag(111)"
18:15	**Paweł Sobieszczyk** - Institute of Nuclear Physics Polish Academy of Sciences, Poland - "Topological magnon gap engineering in van der Waals CrI3 monolayer"
18:30	**Rodrigo Arias** - University of Chile, Chile - "Scattering of magnetostatic surface modes of ferromagnetic films by geometric defects"

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Thursday 11 July

Chair	***Peter Fischer***
08:45 - 09:15	**Valeria Lauter -** Oak Ridge National Laboratory, USA - "Quasi-two-Dimensional Chromium Telluride: Thickness Dependent magnetism and Strain-tunable Berry curvature"
09:15	**Jens Herfort** - PDI Berlin, Germany - "Magnetic properties of Fe_3Si/α-$FeGe_2$/Fe_3Si multilayer films "
09:30	**Sandeep Kumar Chaluvadi** - CNR - IOM, Italy - "Unveiling Room-Temperature Ferromagnetism in 2D Van der Waals Material: Cr4Te5"
09:45	**Wulf Wulfhekel** - Karlsruhe Institute of Technology , Germany - "Magnon-Phonon coupling in Fe_3GeTe_2"
10:00	**Marek Przybylski** - AGH University of Krakow, Poland - "Magnetotransport in 3D and 2D nonstoichiometric and Mn-doped Bi2Te3 "
10:15	**Armando Pezo** - Laboratoire Albert Fert, France - "Spin- and orbital-charge conversion at the surface states of Bi1-xSbx Topological insulators"
10:30 - 11:00	***C O F F E E B R E A K***
Chair	***Giovanni Carlotti***
11:00 - 11:30	**Dirk Grundler** - EPFL, Switzerland - "3D nanomagnetism and magnon modes in ferromagnetic nanotubes, screws and 3D magnonic crystals fabricated by atomic layer deposition"
11:30	**Helmut Schultheiss** - Helmholtz-Zentrum Dresden-Rossendorf, Germany **- "**Floquet magnons in a periodically driven magnetic vortex "
11:45	**Pietro Micaletti** - University of Ferrara, Italy - "Spin wave dispersions in ferromagnetic films with a sinusoidal magnetization distribution in achiral and chiral symmetry"
12:00	**Ryusuke Hisatomi** - Kyoto University, Japan - "Angular momentum transfer in interaction of Laguerre-Gaussian beams with ferromagnetic magnons"
12:15 - 12:45	**Daniela Petti** - Physics Department - Politecnico di Milano, Italy - "Three-dimensional spin-wave dynamics, localization and interference in a synthetic antiferromagnet"
12:45 - 14:15	***LUNCH BREAK***
14:15 - 15:45	**Poster Session - III**
Chair	***Shinji Yuasa***
15:45 - 16:15	**Isabella Boventer** - Laboratoire Albert Fert, France - " Magnonics In Collinear and Canted Antiferromagnets: From Spin-Pumping To Magnon-Photon Coupling "
16:15	**Shoya Sakamoto** - The University of Tokyo, Japan - "Electrical control and detection of chiral spin rotation in Mn3Sn"
16:30	**Akashdeep Akashdeep** - JGU Mainz, Germany - "Epitaxial growth of RuO2 and altermagnetic features in RuO2/FM heterostructure thin films"
16:45	**Matthias Opel -** WMI Garching, Germany - "Magnetic anisotropy and magnon spin transport in antiferromagnetic α-Fe2O3 thin films"
17:00 - 17:30	***C O F F E E B R E A K***
Chair	***André Thiaville***
17:30 - 18:00	**Satoshi Iihama**- Nagoya University, Japan - "Photon-helicity excitation of magnetization dynamics in ferromagnetic metals"
18:00	**Zorica Konstantinovic** - Institute of Physics Belgrade, Republic of Serbia - "Spin-charge conversion in La1-xSrxMnO3/SrIrO3 heterostructure"
18:15	**Christopher Marrows** - University of Leeds, UK - "Temperature gradient-driven motion of magnetic domains in a chiral magnetic metal multilayer"
18:30	**Hao Wu** - Songshan Lake Materials Laboratory, China - "Magnetic memory driven by topological insulators"
20:00	***Social dinner***

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Friday 12 July	
Chair	***Katrin Schultheiß***
08:45 - 09:15	**Stefano Bonetti -** Ca' Foscari University of Venice, Italy - "Terahertz magnetism in ferromagnetic thin metallic films"
09:15	**Roman Adam** - Research Centre Julich, Germany - "THz amplitude control in exchange-coupled Ta/Fe/RuNi spintronic emitter"
09:30	**Simone Laterza** - Elettra Sincrotrone S.C.p.A., Italy - "All-optical spin injection in silicon revealed by element-specific time-resolved Kerr effect "
09:45	**Marco Malvestuto** - Elettra Sincrotrone S.C.p.A., Italy - "The MagneDyn beamline at the FERMI free electron laser"
10:00	**Oksana Chubykalo-Fesenko** - Instituto de Ciencia de Materiales de Madrid - CSIC, Spain - " Ultrafast manipulation of antiferromagnetic order and domain wall dynamics by novel laser torques in Mn_2Au "
10:15	**Kenji Nawa** - Mie University, Japan - "Controllable THz antiferromagnetic resonance frequency in NiO by cation doping: First-principles study"
10:30 - 11:00	***C O F F E E B R E A K***
Chair	***Stefano Bonetti***
11:00 - 11:30	**Jack Gartside** - Imperial College London, UK - "Ultrastrong Magnon-Magnon Coupling and Magnon Frequency Combs in a Dipolar Multilayered '3D' Artificial Spin Ice"
11:30	**Marta Brioschi** - University of Milan, CNR - IOM, Italy - "Coherent and dissipative magnetoelastic coupling in a Fe(10nm)/Py(10nm) nanowire array"
11:45	**Moojune Song** - KAIST, South Korea - "Time-domain measurement of hybrid magnonic system based on superconducting microwave circuit"
12:00	**Albrecht Jander** - Oregon State University, USA - "Modelling non-collinear parametric pumping of forward volume spin waves by surface acoustic waves "
12:15	**Karine Dumesnil -** IJL - Université Nancy, France - "Proximity effects in magnetic/superconductor epitaxial heterostructures with magnetic noncollinearity **"**
12:30 - 13:15	**Closing & prizes** **Chairs: Francesca Casoli, Gianluca Gubbiotti**

Plenary talks

Mapping and controlling three dimensional spin textures

Claire Donnelly[a]

[a] Max Planck Institute for Chemical Physics of Solids

Three dimensional magnetic systems promise significant opportunities for applications, for example providing higher density devices and new functionalities associated with complex topology and greater degrees of freedom [1,2]. Extending to three dimensions allows for the formation of new topologies of spin textures, for example containing defects in 3D such as Bloch point singularities, or truly three-dimensional topological structures such as magnetic torons or hopfions.

In this talk, I will address two main questions: first, can we observe and understand such three-dimensional topological magnetic textures, and second, can we control them?

For the observation and understanding of these three-dimensional textures, we have developed magnetic X-ray tomographic techniques, that open the possibility to map both the three-dimensional magnetic structure [3], and its dynamical response to external excitations [4,5]. In this way, we have observed 3D magnetic solitons which we identify as nanoscale magnetic vortex rings, as well as torons that contain Bloch point singularities [6,7].

However, while X-ray magnetic tomography is now a relatively well-established technique, high resolution imaging of extended magnetic systems has so far been limited to rare-earth containing materials. To this end, I will present recent results of soft X-ray dichroic ptychography where the phase dichroism offers a route to imaging magnetic systems that until now have not been accessible [8].

As well as naturally existing within the bulk, 3D spin textures can be introduced and *controlled* via the patterning of 3D curvilinear geometries [9]. I will discuss how, in this way, not only can new states be realized [10], but the energy landscape of topological defects can be designed through the local patterning of curvature induced chirality [11].

This new understanding and control of topological textures in 3D magnetic systems paves the way not only for enhanced understanding of these systems, but also towards the next generation of technological devices.

[1] Fernández-Pacheco et al., Nature Communications 8, 15756 (2017).

[2] C. Donnelly and V. Scagnoli, J. Phys. D: Cond. Matt. 32, 213001 (2020).

[3] C. Donnelly et al., Nature 547, 328 (2017).

[4] C. Donnelly et al., Nature Nanotechnology 15, 356 (2020).

[5] S. Finizio et al., Nano Letters (2022)

[6] C. Donnelly et al., Nat. Phys. 17, 316 (2021)

[7] N. Cooper, PRL. 82, 1554 (1999).

[8] Neethirajan et al., arXiv:2309.14969 (*Accepted by PRX*)

[9] D. Sheka, APL 118, 230502 (2021)

[10] C. Donnelly et al., Nature Nanotechnology 17, 136 (2022)

[11] S. Ruiz Gomez et al., arXiv.2404.06042 (*In review*)

Superconducting diode effect in superconductor/ferromagnet multilayers

Teruo Ono[a,b]

[a] Institute for Chemical Research, Kyoto University, Japan
[b] Center for Spintronics Research Network, Kyoto University, Japan

The diode effect is fundamental to electronic devices and is widely used in rectifiers and AC-DC converters. However, conventional diodes have an energy loss due to finite resistance. We found the superconducting diode effect (SDE) in Nb/V/Ta superlattices with a polar structure, which is the ultimate diode effect exhibiting a superconducting state in one direction and a normal state in the other [1-3]. SDE can be considered as the nonreciprocity of the critical current for the metal-superconductor transition. We also found the reverse effect, i.e., the nonreciprocal critical magnetic field under the application of the supercurrent [4]. We also found that the polarity of the superconducting diode shows a sign reversal as a magnetic field is increased [5], which can be considered as the crossover and phase transitions of the finite-momentum pairing states predicted theoretically [6]. SDE in Nb/V/Ta superlattices needs an application of an external magnetic field to break the time reversal symmetry, which is a disadvantage in applications. We recently succeeded in demonstrating SDE in a zero-field by introducing ferromagnetic layers in superlattices [7, 8]. The polarity of the SDE is controlled by the magnetization direction of the ferromagnetic layer, leading to development of novel non-volatile memories and logic circuits with ultralow power consumption.

This work was partly supported by JSPS KAKENHI Grant Numbers (18H04225, 18H01178, 18H05227, 20H05665, 20H05159, 21K18145), MEXT Initiative to Establish Next-generation Novel Integrated Circuits Centers (X-NICS) Grant Number JPJ011438, the Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University, and the Collaborative Research Program of the Institute for Chemical Research, Kyoto University.

[1] F. Ando et al., J. Magn. Soc. Japan 43, 17 (2019).

[2] F. Ando et al., Nature 584, 373 (2020).

[3] F. Ando et al., Jpn. J. Appl. Phys. 60, 060902 (2021).

[4] Y. Miyasaka et al., Appl. Phys. Express 14, 073003 (2021).

[5] R. Kawarazaki et. al., Appl. Phys. Express 15 113001 (2022)

[6] A. Daido et al., Phys. Rev. Lett. 128, 037001 (2022).

[7] H. Narita et al., Nat. Nanotechnol. 17, 823 (2022).

[8] H. Narita et al., Adv. Mater., 10.1002/adma.202304083.

Women and science: an overview of data, open questions and possible solutions

Sveva Avveduto

National Research Council, Rome, Italy

Women and Science Association, Rome, Italy

The seminar will focus on the themes of women's participation in the scientific enterprise in its various aspects.

Some data and figures will be presented regarding university education and the presence of researchers in the STEM areas and in the international context. These figures assess their limited presence in the area so the talk will refer to some initiatives for a possible overcoming of the gender gap in careers starting from the single institution up to the implementation of a broader scientific policy.

The themes of gender bias and stereotypes that still hinder women participation will be included as well. The activities of international organizations will be presented and discussed such ad the G20 and G7 in their specific engagement groups Women20 and Women7, as well as the activities of natioal organizations and specific dedicated projects.

Invited talks

Altermagnets: An unconventional magnetic class

Tomas Jungwirth

Institute of Physics, Czech Academy of Sciences, Cukrovarnická 10, 162 00 Praha 6, Czech Republic

School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom

Conventional magnets can be divided in two basic classes – ferromagnets and antiferromagnets. In the first part of the talk, we will recall that the ferromagnetic order offers a range of phenomena for energy efficient IT, while the vanishing net magnetization in antiferromagnets opens a possibility of combining ultra-high energy efficiency, capacity and speed of future IT [1-4]. In the main part of the talk we will move on to our recent predictions of instances of strong time-reversal symmetry breaking and spin splitting in electronic bands, typical of ferromagnetism, in crystals with antiparallel compensated magnetic order, typical of antiferromagnetism [5-8]. We resolved this apparent fundamental conflict in magnetism by symmetry considerations that allowed us to classify and describe a third basic magnetic class [6,7]. Its alternating spin polarizations in both crystal-structure real space and electronic-structure momentum space suggested a term altermagnetism. A d-wave spin-polarization order in altermagnets is a direct counterpart of the unconventional d-wave superconducting order in cuprates. We will discuss predictions and initial experimental verifications [9,10] in which altermagnets combine merits of ferromagnets and antiferromagnets, that were regarded as principally incompatible, and have merits unparalleled in either of the two conventional magnetic classes. We will introduce the broad materials landscape of altermagnetism and show how its unconventional nature enriches fundamental concepts in condensed matter physics, such as the Kramers theorem [10]. We will show that this underpins a development of a new avenue in spintronics, elusive within the two conventional magnetic classes, based on strong and conserving spin phenomena, without magnetization imposed scalability limitations.

[1] P. Wadley, T. Jungwirth *et al.*, Science 351, 587 (2016)
[2] T. Jungwirth *et al.*, Nature Nanotech. 11, 231 (2016)
[3] Z. Kaspar, T. Jungwirth *et al.*, Nature Electron. 4, 30 (2021)
[4] F. Krizek T. Jungwirth *et al.*, Science Adv. 8, eabn3535 (2022)
[5] L. Smejkal, T. Jungwirth *et al.*, Science Adv. 6, eaaz8809 (2020)
[6] L. Smejkal, T. Jungwirth *et al.*, Nature Rev. Mater. 7, 482 (2022)
[7] L. Smejkal, J. Sinova, T. Jungwirth, Phys. Rev. X 12, 031042 (2022)
[8] L. Smejkal, J. Sinova, T. Jungwirth, Phys. Rev X (Perspective) 12, 040501 (2022)
[9] Z. Feng, T. Jungwirth *et al.*, Nature Electron. 5, 735 (2022)
[10] J. Krempasky, T. Jungwirth *et al.*, Nature 626, 517 (2024)

Advanced Magnetic Imaging at the nanoscale

Agustina Asenjo

Institute of Material Science of Madrid-CSIC, Spain

In recent decades, magnetic imaging techniques have undergone significant development, mainly focusing on enhancing lateral resolution and sensitivity, including achievements as the single-spin detection [1]. Beyond these milestones, crucial objectives are quantification of the magnetic moment and the detailed description of domain wall configurations [2,3] and its dynamics, being this last frequently reduced to the scope of micromagnetic simulations. Magnetic force microscopy (MFM) has emerged as a widely adopted characterization technique utilized in a variety of research and industrial applications. Despite notable advances [4] in MFM, such as resolution down to 10nm, adaptability to various environments as liquids [5] and applied magnetic fields [6], as well as the generation of quantitative MFM images [4] or the probe-engineering developments [7], certain challenges persist.

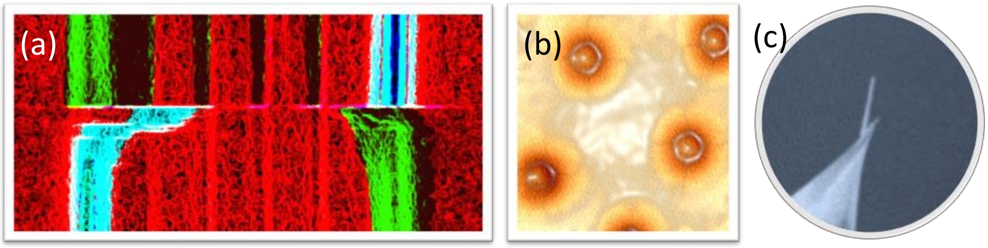

Figure: (a) Non-standard MFM image used for the magnetization reversal study, (b) MFM image of a Py dot with skyrmionic configuration, (c) SEM image of an MFM probe based on Fe nanorod [7]

In the current landscape, characterizing devices based on magnetic materials demands the ability to operate under real-world conditions. Remarkable progress has been made through "in situ" characterization, enabling a deeper understanding of the complex magnetization processes in nanostructures. However, relevant magnetic imaging must satisfy the possibility of combine high spatial resolution and high sensitivity with the “in operando” measurements [8].

This work aims to present a review of the most significant developments in Magnetic Imaging, particularly focusing on MFM, while also exploring the future perspectives and potential advancements in the technique.

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Experimental demonstration of a skyrmion-enhanced strain-mediated physical reservoir computing system

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Reservoir computing (RC), in which only the output weights need to be trained, is computationally one of the lowest cost artificial recurrent neural networks (RNNs) [1-3]. Physical reservoirs holding intrinsic nonlinearity, high dimensionality, and memory effects have attracted considerable interest regarding solving complex tasks efficiently [4]. Particularly, spintronic and strain-mediated physical reservoirs are appealing due to their high speed, multi-parameter fusion and low power consumption [5,6]. Here, we experimentally realize a skyrmion-enhanced strain-mediated physical reservoir in a multiferroic heterostructure of Pt/Co/Gd multilayers on (001)-oriented 0.7PbMg1/3Nb2/3O3-0.3PbTiO3 (PMN-PT), as shown in Fig. 1. The enhancement is coming from the fusion of magnetic skyrmions and electro resistivity tuned by strain simultaneously. The benchmark task of Mackey-Glass time series prediction is performed, and normalized root mean square error (NRMSE) of 0.2 for a 20-step prediction is achieved. Furthermore, we explore the temporal and spatial co-multiplexing reservoir, the NRMSE is reduced by more than half for the 20-step prediction, indicating the significant improvement of computational power. Our work lays the foundations for low-power neuromorphic computing systems with magneto-electro-ferroelastic tunability, representing a further step towards developing future strain-mediated

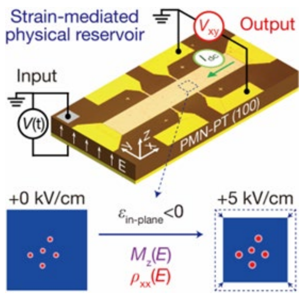

Figure 1: Schematic diagrams of the experimental method and the skyrmion-enhanced strain-mediated RC system.

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Induced anisotropies and flux closure in self assembled, rolled magnetic membranes

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The configuration of magnetic domains is crucial for the functionality of magnetic devices, and hence the possibility of tailoring them is subject of intense investigations. In addition to tailoring domains with bulk and interface anisotropies, modifying sample geometry and especially curving a formerly flat membrane into a tube is of recent interest [1, 2]. In the case of nanotubes, e.g., azimuthal flux closure allows the formation of a vortex domain wall (DW), which is predicted to possess a much larger DW velocity than the transverse DW in flat nanowires.

In the present work, we aim at azimuthal domain configurations in rolled permalloy (Py) membranes, solely induced by partial flux closure. To that end, Py membranes are prepared on a polymer platform, which can be self-assembled rolled either upwards or downwards. To exclude possible magnetoelastic anisotropy contributions, which occur for a non-vanishing magnetostriction [2], a Py composition close to the compensation point has been used, and membranes have been curved both up- and downwards. We observe a clear transition from an axial magnetization configuration in the flat membrane into an azimuthal configuration, when membranes are rolled – irrespective of the rolling direction (or strain state). It depends, however, on the degree of flux closure controlled by membrane width W and tube diameter D.

These studies are the first experimental realization of a purely flux closure induced azimuthal anisotropy in rolled membranes and are thoroughly supported by analytical micromagnetic calculations.

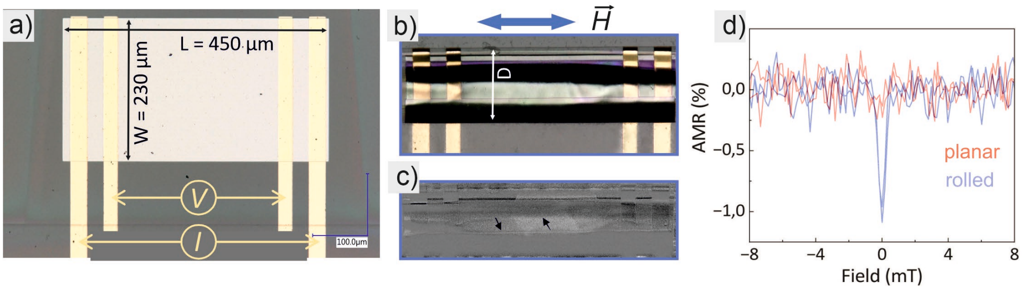

Figure 1: a) Py-membrane on rollable polymer platform with Au-contacts for 4-point anisotropic magnetoresistance (AMR) measurements; b) after self-assembled rolling into a 110 µm diameter tube; c) Kerr micrograph on dome of tube displaying azimuthal domains; d) AMR measurements indicating a change from parallel to azimuthal anisotropy upon rolling the membrane.

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Vertex Frustration and Exotic Behaviors in Artificial Spin Ice

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Artificial spin ices [1,2] are frustrated arrays of interacting nano islands whose magnetic state can be approximated by an Ising spin. They have the advantage of being designable and characterizable at the constituent degree of freedom. While early realizations attempted to reproduce properties and phenomena of existing magnetic spin ices [1,2], the aim was always to produce by nano fabrication magnets of unusual properties often not found in natural materials. In 2013 [3], our team at Los Alamos introduced the concept of "vertex frustration" for these materials, which allowed for the design and realization of a plethora of new nano magnets of distinct and exotic properties. We will report on the recent advancements stemming from this program, highlighting three novel nanomagnets conceived at Los Alamos and materialized by the research group led by Peter Schiffer at Princeton. Specificall: We will discuss: Shakti spin ice [3,4,5,6], which realizes the ice rule in emergent form and a classical topological phase in the form of an emergent dimer model; Tetris spin ice, showcasing a reduction in magnetic texture dimensionality and kinetics [7], while revealing the counterintuitive concept of "entropy-driven order" at equilibrium [8]. And finally Santa Fe spin ice [3], where nanomagnets can be conceptualized within a string framework [9], illustrating a thermal crossover between topologically trivial and non-trivial kinetics of its emergent strings [10]. These advancements mark significant progress in harnessing artificial spin ice to create magnets with unique properties rarely found in natural magnets.

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Thermo-spin effects in nanostructured ferromagnetic thin films

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The correlation between spin and charge in electronic transports has been energetically studied in a scheme of spintronics research. Recently, the coupling between heat current, spin current and charge current is also attracting much attention, and this newly established filed is called “spin caloritronics”. The Nernst effect is a common thermomagnetic effect, which has been known for a long time. When a temperature gradient is applied on a material with spontaneous magnetization, an electric field is induced in the perpendicular direction to both the temperature gradient and the magnetization, which is called the anomalous Nernst effect (ANE). We have reported ANE measurements of an $L1_0$-ordered epitaxial FePt thin film, which is a well-known material with a large magnetic anisotropy, for studying thermomagnetic effects in ordered alloys [1]. We also studied the material dependence of ANE regarding the spin-orbit interaction in several perpendicularly magnetized ordered-alloy thin films [2]. The ANE has some advantages against the Seebeck effect, which is widely used as a thermoelectric power generation element, does not have. Therefore, it is expected that the ANE can be applied to high-performance thermoelectric energy conversion elements by strategical designing [3]. Obtaining materials with a large ANE is indispensable to realize a practical application of ANE-based energy conversion as shown in Fig. 1. From this point of view, this talk describes our study on the ANE in various nanostructured magnetic materials. The enhancement of ANE for granular thin films and multilayers, FePt films with spin-wave contribution, and spin caloritronic devices with magnetic nanostructures for ANE-based thermoelectric energy conversion will be discussed [4-9].

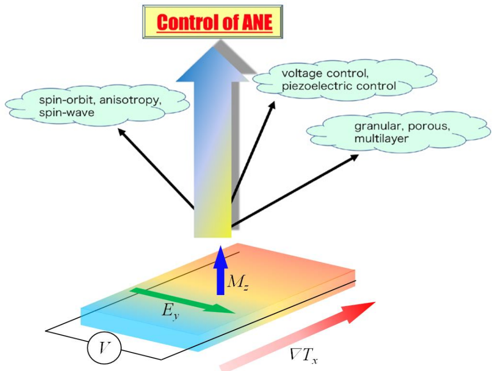

Figure 1: Schematic image of strategy to control and enhance ANE.

This research was supported by JST-CREST (JPMJCR1524) and Grant-in-Aid for Scientific Research (S) (21H05016) from Japan Society for the Promotion of Science.

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Spin-orbit torque driven domain wall motion in the absence of Dzyaloshinskii-Moriya interactions

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A series of recent studies of ultrathin (insulating) garnet films with perpendicular magnetization, capped by platinum along which current is fed, have reported magnetization switching and domain wall motion [1]. Interfacial Dzyaloshinskii-Moriya interaction (DMI) has been invoked to explain these results, although (i) there is at present no mechanism to account for an interfacial DMI at the surface or interface of an insulating garnet (ii) conflicting experiments attribute this interfacial DMI to the garnet substrate\garnet film interface, or to the garnet\platinum interface (iii) the observed DMI values are quite weak, the in-plane fields sufficient to suppress their effect being of only a few milli-Tesla. Being epitaxial, garnet films possess a cubic magnetocrystalline anisotropy. The role of this secondary anisotropy on the structure of the DWs, and on their motion under spin-orbit torque (SOT) therefore needs to be evaluated. Indeed, the secondary anisotropy competes with magnetostatics so that the domain walls are no longer of the pure Bloch type.

We performed a micromagnetic study of the role of a secondary anisotropy on the damping-like SOT motion of domain walls. Both the garnet cubic anisotropy for (111) films, and a – simpler - orthorhombic anisotropy, to be found e.g. in Co/W(110), have been considered. Due to the very different distribution of secondary easy axes, the two systems are qualitatively different. Yet, using the parameters of thulium iron garnet, we obtain in both cases non-negligible velocities, with two possibilities at small currents corresponding to the domain wall initial structures (fig. 1). In the orthorhombic case, an analytic model could be built, which compares well with one-dimensional numerical micromagnetics.

The physics behind this motion will be explained, as well as the role of ~~all~~ sample parameters. This study provides another source of explanation for the current-induced domain wall motion in ultrathin garnet films, as sketched in a recent study [2].

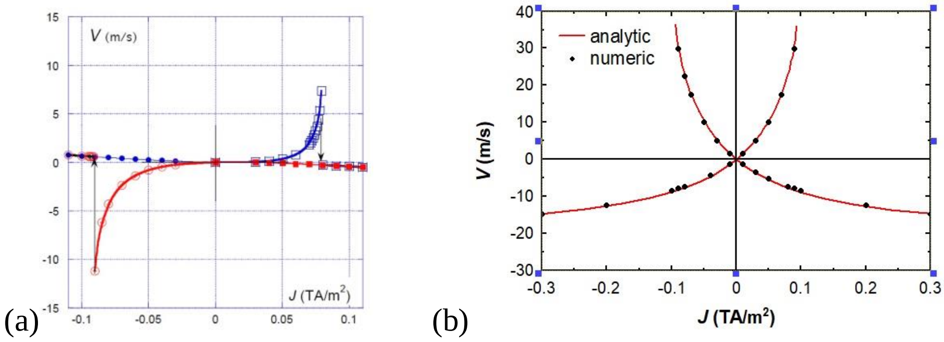

Figure 1: Steady-state velocity of a domain wall driven by DL-SOT, for a cubic anisotropy (a), and an orthorhombic anisotropy (b). Current flows at 15° from direction [1-10] (a), and at 60° from the in-plane easy axis (b). Gilbert damping α= 0.5.

Work supported by French National research agency (DeMIuRGe, ANR-22-CE30-0014).

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Oxide Materials for Spintronics

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For magnetic oxides, competition between various types of exchange interactions has often led to striking physical properties that are highly tunable by external fields. Such tunability is desirable for spintronic applications. In this talk, I will show how one can use electric field to control magnetic domain structures and interfacial ferroelectricity in oxides thin films and heterostructures, giving rise to the ability to control spin-dependent transport using electric field. The electric field control of magnetic domain structures in oxides is achieved based on the understanding of the physical origin of domain formation in oxides, which is well beyond conventional Landau-Lifshitz theory. We have successfully fabricated various oxides-based spintronic devices, which all exhibit promising functionality with low energy consumption. To finish, I will discuss the future of oxides spintronics from my own perspective.

Ab initio exploration of graphene intercalated lanthanides

Gustav Bihlmayer

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Intercalating lanthanides between graphene and a suitable substrate offers the possibility to realize stable, two-dimensional magnetic systems: large magnetic anisotropies of the 4*f* atoms or coupling to a magnetic substrate provide the energy barrier to protect the systems from spin fluctuations. In addition, the induced magnetism in the graphene allows studying topological phases with interesting transport properties. In this talk, density functional theory calculations with appropriate extensions of several material combinations will be discussed and comparison to experiments will be shown.

Europium can be intercalated between graphene and magnetic surfaces like Co(0001) or Ni(111) forming a $\sqrt{3} \times \sqrt{3}$ layer [1]. The doping of graphene can create a pronounced flat band at the Fermi level and the interaction of the 4*f* states with the π band of graphene leads to spin-selective hybridization and opening of the Dirac cone with interesting consequences for edge channels. This system can be compared to Eu on-top of a graphene covered Co substrate, that changes the magnetic coupling between the lanthanide and the substrate [2] and modifies the graphene's interaction with the 4*f* states (see fig. 1). Further stacking combinations are possible and will be discussed.

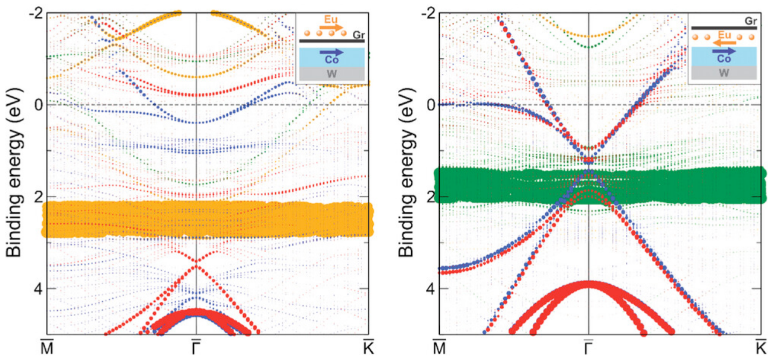

Figure 1: Band structure of Eu/graphene/Co(0001) (left) and graphene/Eu/Co(0001) (right). The majority/minority states of graphene and Eu are shown in blue/red and orange/green, respectively (from Ref. [2]).

Finally, the magnetism of open-shell 4*f* atoms on graphene will be investigated and compared to the closed shell counterparts like Eu or Gd [3]. The large magnetic anisotropies observed there will open new possibilities on non-magnetic substrates.

I want to thank my collaborators in these works, M. Jugovac, P. Perna, P. M. Sheverdyaeva, L. Ferrari, J. P. Carbone, J. Bouaziz, N. Atodiresei, and S. Blügel and for funding from the FLAG-ERA grant SOgrapMEM and from CRC 1238 of the Deutsche Forschungsgemeinschaft.

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Quasi-two-Dimensional Chromium Telluride: Thickness Dependent magnetism and Strain-tunable Berry curvature

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In recent years, a variety of novel two-dimensional (2D) van der Waals magnets have been discovered, founding the active field of 2D magnetism [1]. Among these prospective compounds, binary chromium tellurides $Cr_{1-\delta}Te$ are attractive owing to their rich magnetic properties, as well as inherent chemical and structural compatibility when forming heterostructures [2] with other topological systems. Magnetic transition metal chalcogenides form an emerging platform for exploring spin-orbit driven Berry phase phenomena owing to the nontrivial interplay between topology and magnetism. Here we show that the anomalous Hall effect in pristine Cr_2Te_3 thin films manifests a unique temperature dependent sign reversal at nonzero magnetization, resulting from the momentum-space Berry curvature as established by first-principles simulations. The sign change is strain tunable, enabled by the sharp and well-defined substrate/film interface in the quasi-two-dimensional Cr_2Te_3 epitaxial films, revealed by scanning transmission electron microscopy and depth-sensitive polarized neutron reflectometry. This Berry phase effect further introduces hump-shaped Hall peaks in pristine Cr_2Te_3 near the coercive field during the magnetization switching process, owing to the presence of strain-modulated magnetic layers/domains [3]. The versatile interface tunability of Berry curvature in Cr_2Te_3 thin films offers new opportunities for topological electronics.

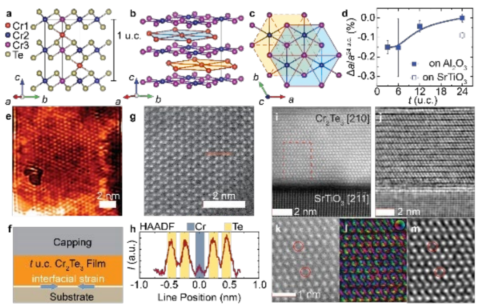

Figure 1. **a**, Atomistic structure of Cr_2Te_3 along [210] direction. **b**, three Cr species, with six-fold in-plane symmetry (**c**). **d**, Enhanced in-plane compressive strain at reduced thickness t. **f**, Schematic of the film stacks. Atomically resolved STM morphology (**e**) and planar HAADF STEM image (**g**) of Cr_2Te_3 confirm the honeycomb-like Te lattice and Cr sites (**h**). **i**-**m**, Cross-sectional images of Cr_2Te_3 films on $SrTiO_3$(111). The HAADF (**i**) and iDPC (**j**) imaging. The enlarged view of HAADF (**k**), DPC (**l**), and iDPC (**m**) images identify the random distribution of the interlayer Cr1 (circles), which deviates from the ideal Cr_2Te_3 structure with full occupancy.

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3D nanomagnetism and magnon modes in ferromagnetic nanotubes, screws and 3D magnonic crystals fabricated by atomic layer deposition

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Magnons can serve as information carriers and enable charge-free signal processing in nanoscale microwave electronics operating at ultrahigh frequencies. They allow for wave-based logic in free-form 3D nanoarchitectures. However experiments on magnons in 3D ferromagnetic nanoarchitectures are at their infancy due to a technology gap in large-scale nanofabrication. We have optimized the industrially relevant atomic layer deposition (ALD) of ferromagnetic metals such as Ni [1,2] and $Ni_{80}Fe_{20}$ [3,4] and achieved conformal coatings with unprecedented qualities concerning specific resistivity, anisotropic magnetoresistance effect and low damping of spin waves. Thereby we produce free-form 3D ferromagnetic nanostructures consisting of individual or interconnected tubular ferromagnetic shells which are curved in all three spatial directions. The 3D nanostructures have large footprints and are fabricated on either semiconductor nanotemplates [1,3,4] or polymeric networks produced by two-photon lithography [2]. The ALD-grown shell thicknesses range from about 10 to 30 nm. Diameters of tubes and tubular segments vary between 100 nm and about 1500 nm. Lattice constants in 3D magnonic crystals are varied from about 500 nm to 2000 nm. We report on the local spin-wave spectroscopy between about 2 and 40 GHz and micromagnetic simulations addressing the distinct magnon modes that we observe in nanotubes [1,3,4], screws [5] and 3D woodpile nanoarchitectures [2] consisting of either Ni or $Ni_{80}Fe_{20}$ shells. We report on our latest experiments in 3D nanomagnetism which explore magnetochiral effects, novel surface magnon modes in 3D magnonic crystals and nonreciprocal spin-wave dispersion relation induced in thin Ni via a 3D screw-like curvature. The work was realized in cooperation with M.C. Giordano, H Guo, A.J.M. Deenen, M. Xu, A. Toros, D. Bouvet, B. Bártová, R. Therisod, D.F. Reyes Vasque, M Hamdi, K. Baumgaertl, S. Watanabe, A. Mucchietto, S.E. Steinvall, J. Gay, M. Vuichard, and A. Fontcuberta i Morral. This research is supported by the SNSF via grant number 197360.

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Three-dimensional spin-wave dynamics, localization and interference in a synthetic antiferromagnet

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The three-dimensional nature of wave phenomena in condensed matter profoundly influences various disciplines in nanoscience, spanning acoustics, nano-optics, and plasmonics. In the realm of spin waves, three-dimensionality is intrinsic in their phenomenology and is the subject of growing interest in magnonics [1]. Despite this, the experimental visualization of propagating spin waves in three dimensions has been elusive, due to the harsh requirement of combining nanoscale spatial resolution in 3D, and time resolution across the GHz frequency range. In this framework, recently, we used Time-Resolved Soft X-Ray Laminography (TR-SoXL) [2] to reveal the full three-dimensional structure of spin waves propagating in a synthetic antiferromagnet (SAF).

Our sample consists of a NiFe 40/Ru 0.9/CoFeB 50 (nm) SAF microstructure, in which spin waves are emitted by nanoscale spin textures (see Fig. 1), i.e. vortices and domain walls [3] stabilized at 0 field. By mapping both the in-plane and out-of-plane components of the magnetization, we fully reconstruct the precessional dynamics associated to propagating spin waves, with nanoscale spatial resolution across the plane and through the volume of the sample. We find non-uniform spin-wave mode profiles, indicating the localization of the spin waves, that lead to the generation of complex three-dimensional features due to spin-wave interference, which we reveal experimentally and analyze with micromagnetic simulations [4].

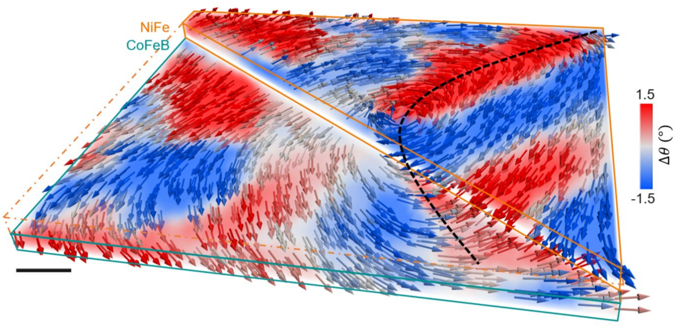

Figure 1: Reconstruction of the three-dimensional magnetization dynamics (arrows) in NiFe and CoFeB. The blue/red colour-code refers to the in-plane dynamics. The dashed line corresponds to a domain wall emitting spin waves. Scale bar: 200 nm.

This work opens the way to the direct visualization, study and control of nanoscale spin waves in three-dimensions, and of their interactions in thin films and nanostructures. This in turn allows the design of novel functionalities in next generation magnonic devices.

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Magnonics In Collinear and Canted Antiferromagnets: From Spin-Pumping To Magnon-Photon Coupling

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Recent years have been the frame of a renewal of activity of magnonic and spintronic research on antiferromagnetic (AFM) materials due to some of their intrinsic and potentially advantageous properties [1]. Their vanishing stray fields, higher resonance frequencies, and the possibility to control them by spin currents renders them scalable, fast and tunable for future ICT devices. However, the implementation of magnonic AFM devices requires a profound understanding of the spin dynamics of AFMs and of their ability to couple to other systems to be integrable with other platforms. Despite huge progress, the capacity to generate coherent and sizeable electrical signal from their magnetization dynamics, and to couple efficiently with photonic excitation in cavities remain mainly elusive. In this contribution, we will first report on our latest results on the investigation of inverse spin Hall effects generated by AFM resonances and ultra-fast spin wave propagation using hematite Fe_2O_3 as model systems [2,3]. In parallel, we discuss on the dynamics of antiferromagnets and how they can strongly couple with cavity photons and form AFM cavity magnon polaritons. We evidence that the presence of DMI in the canted phase of Hematite leads to an enhanced spin pumping signal as well as an increase of the magnon-cavity photon coupling strength compared to the collinear phase, achieving cooperativities C>70 for the canted phase [4]. These results pave the way to integrate canted AFMs in future AFM magnonic devices and for information processing with cavity magnonics

Acknowledgements
I.B. and R.L acknowledge support from the French Agence Nationale de la Recherche (ANR) under grant ANR-22-CE24-0008-03 (ICARUS). R.L., I. B., A.A. and M.K. acknowledge financial support from the Horizon 2020 Framework Programme of the European Commission under FET-Open grant agreement no. 863155 (s-Nebula). I. B. and R. L. acknowledges financial support from the Horizon 2020 Framework Programme of the European Commission under FET-Open grant agreement No. 964931 (TSAR). M.K. acknowledges support from the Graduate School of Excellence Materials Science in Mainz (MAINZ) DFG 266, the DAAD (Spintronics network, Project No. 57334897). M.K. acknowledges support from the DFG project number 423441604 and 268565370 (Project A01). The Research Council of Norway supported H.T.S., B.B, M.K., and A.B. through its Centers of Excellence funding scheme, project number 262633 “QuSpin”.

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Photon-helicity excitation of magnetization dynamics in ferromagnetic metals

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Photonic control of magnetization direction in thin film metallic ferromagnets has attracted much attention, which might be used for future applications such as photonic-spintronics memory devices [1]. Magnetization switching using circularly-polarized light has been reported in which magnetization direction is determined by photon-helicity. However, this helicity-dependent magnetization switching has been considered to be mainly caused by stochastic thermal process, leading to slower switching dynamics. On the contrary, photonic excitation of magnetization dynamics using direct coupling between light electric field and magnetization such as inverse Faraday effect has been reported recently [2-5], which is promising for ultrafast and energy-efficient magnetization manipulation. Figure 1(a) shows schematic illustration of time-resolved magnetization dynamics measurement where photon-helicity induced magnetization precession can be detected. Phase of magnetization precession is 180 degrees rotated when photon-helicity is reversed as shown in Fig. 1(b), indicating photon-helicity excitation of magnetization dynamics. Photon-helicity induced field-like torque and damping-like torque in ferromagnetic metals can be evaluated by analysing phase of magnetization precession, which will be discussed in the presentation.

This work was partially supported by JST PRESTO (No. JPMJPR22B2), the Asahi Glass Foundation, the Murata Science Foundation, and Advanced Technology Institute Research Grants.

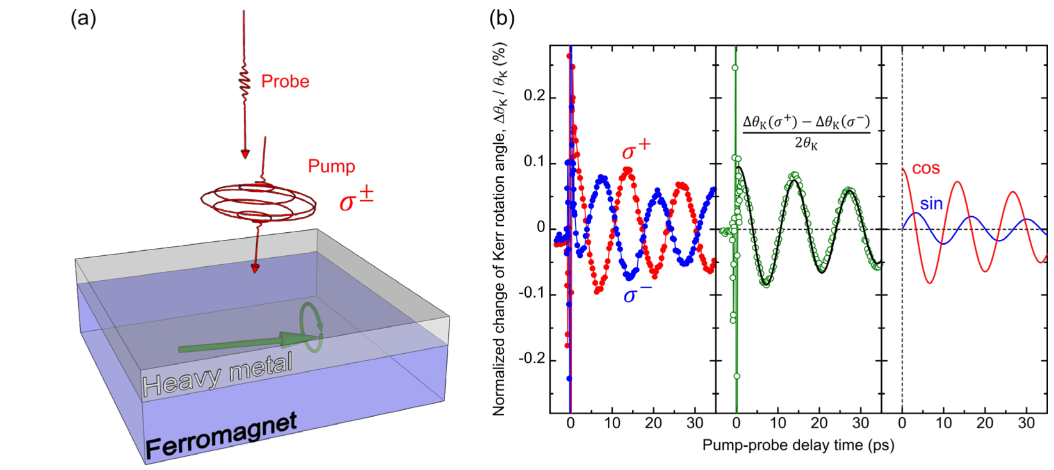

Figure 1: (a) Schematic illustration of photon-helicity induced magnetization dynamics measurement in ferromagnetic thin film. (b) Measurement results of photon-helicity dependent magnetization dynamics in cobalt/platinum bilayer and its analysis [5].

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Terahertz magnetism in ferromagnetic thin metallic films

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The interaction between light and matter is and it has been at the heart of our understanding of condensed matter physics, and of physics at large. Historically, the development of previously unavailable light sources, extending both the achievable wavelength and brightness ranges, have greatly impacted fundamental research and eventually technology, such as for the case of the laser.

In this talk, I will focus on coherent THz radiation of large amplitude, i.e. with electric fields of the order of 1 MV/cm and magnetic fields in the 0.1 – 1 Tesla range, and its interaction with magnetic materials. Thanks to these strong THz fields, we have recently been able to experimentally discover an elusive phenomenon in condensed matter: the evidence of magnetic "nutation" [1,2], predicted over 10 years ago as a consequence of inertia in the Landau-Lifshitz-Gilbert equation, which I will discuss in the presentation. Then, I will present our recent efforts to understand terahertz driven dynamics in thin film layers with different crystalline order [3], and the theoretical investigations to model magnetization switching [4] and spin wave dynamics [5] in the presence of inertia.

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Ultrastrong Magnon-Magnon Coupling and Magnon Frequency Combs in a Dipolar Multilayered '3D' Artificial Spin Ice

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Strongly-interacting nanomagnetic arrays are ideal systems for exploring the frontiers of magnonic control. They provide functional reconfigurable platforms and attractive technological solutions across storage, GHz communications and neuromorphic computing. Typically, these systems are primarily constrained by their range of accessible states and the strength of magnon coupling phenomena. Increasingly, magnetic nanostructures have explored the benefits of expanding into three dimensions. This has broadened the horizons of magnetic microstate spaces and functional behaviours, but precise control of 3D states and dynamics remains challenging. Here, we introduce a 3D magnonic metamaterial (1) compatible with widely-available fabrication and characterisation techniques. By combining independently-programmable artificial spinsystems strongly coupled in the z-plane, we create a system with a rich 16^N microstate space and intense static and dynamic dipolar magnetic coupling. The system exhibits a broad range of emergent phenomena including ultrastrong magnon-magnon coupling with normalised coupling rates of $\Delta\omega/\gamma=0.57$, GHz mode shifts in zero applied field and reconfigurable generation of magnon frequency combs

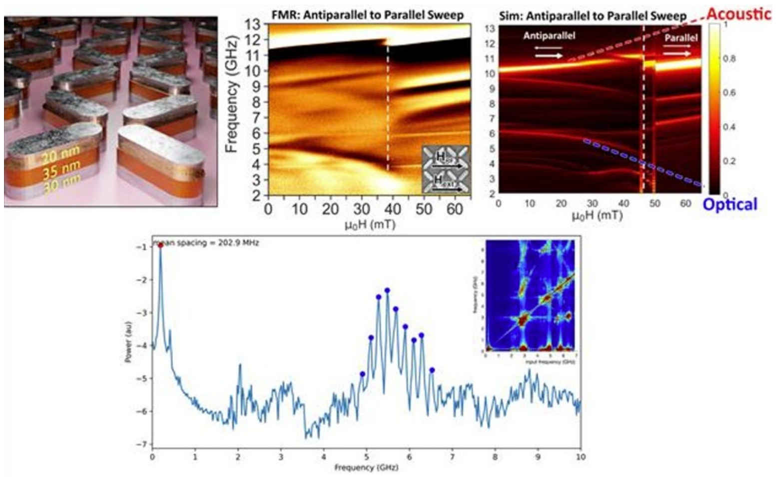

Fig.1 a) Schematic of system b,c) Experimental & simulation frequency/field FMR heatmaps showing ultrastrong magnon-magnon coupling. d) Magnon frequency comb

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25th International Colloquium on Magnetic Films and Surfaces (ICMFS2024)
Perugia, from 7 to 12 July 2024

Oral talks

On the antiferromagnetic-ferromagnetic phase transition in pinwheel artificial spin ice

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Nanopatterned magnetic thin films enable the engineering of myriad magnetic behaviors, such as reconfigurable long-range order. A prominent example is artificial spin ice (ASI), where the geometric arrangement of nanoscale magnetic elements act as macrospins and interact via stray fields.

We focus on the transition from antiferromagnetic (AF) to ferromagnetic (FM) states in square lattice ASI, as the magnetic elements are rotated to a 45° "pinwheel" configuration [1], see Figure 1. Using x-ray magnetic circular dichroism photoemission electron microscopy (XMCD-PEEM) we observe the AF-FM transition directly. The transition takes place at a critical rotation angle of the nanomagnets, which depends on the nanomagnet separation in the lattice. The amount of AF vs. FM order can thus be tuned by geometric design of the ASI system. Our results show that traditional point-dipole models fail to predict the correct transition angle. However, adopting a dumbbell-dipole model achieves excellent agreement with experimental data. This model explains the coupling-dependence of the transition angle, which is not captured by the point-dipole model.

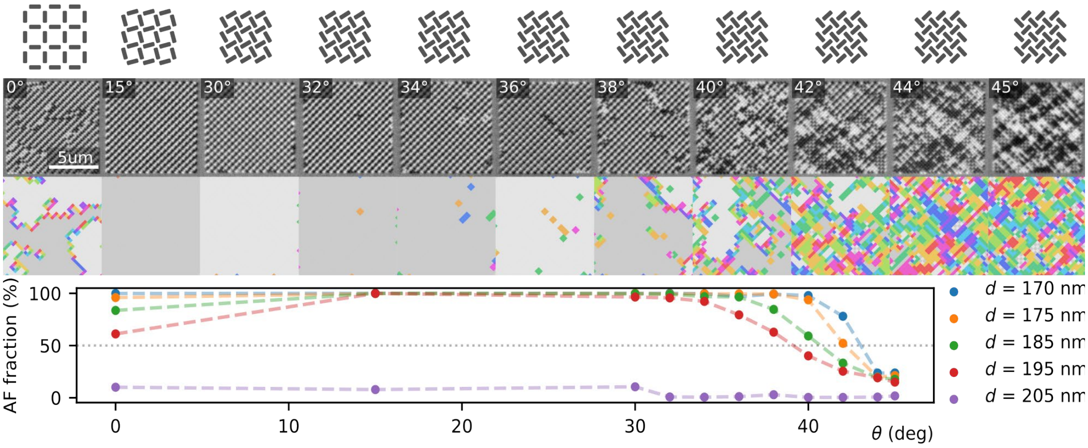

Figure 1: Top row: ASI geometry schematics. Middle rows: XMCD-PEEM images and analysed magnetization orientation. Bottom graph: Fraction of AF-ordered regions for different interisland spacing.

Our findings resolve a discrepancy between measurement and theory in previous work on pinwheel ASIs [2], which suggests that a correction to simulators used in correlated macrospin research is necessary to more accurately model their behavior. Control of the AF–FM transition and this revised model open new pathways for improved design of magnetic order in nanostructured systems.

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Magnetic metamaterials produced by ion implantation

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New and ground-breaking ways to manipulate light in an energy range extending from the visible up to the soft X‐ray regime, utilizing magnetism and diffractive optics, have recently come into focus [1,2]. Several approaches rely on the creation of suitable diffractive optics exploiting modern nanolithography processes, such as Electron Beam Lithography (EBL) [2‐5]. Such devices comprise planar structures with topographical features, which diffract light due to the periodic structuring. When these features are made of a magnetic material, they interact through stray-fields producing a long-range collective magnetic order which can also act as a grating via magneto-optical effects. By applying external stimuli, such as field or temperature, the magnetic configuration can be tuned, leading to a reconfigurable grating. Therefore, even though the lithographically defined structure is "locked‐in", there can be a variety of stable magnetic configurations. As such, magnetism offers ways to reconfigure the function of the gratings, without the need for costly fabrication of new structures. Light scattering from such structures is characterized by two contributions: a strong charge scattering generated from the geometrical structure, and a magnetic signal generated from the reconfigurable long-range magnetic order. However, the strong charge scattering background often masks and limits the functionality of such structures.

To address this issue, we explore the feasibility of ferromagnetic nano-structures made by spatially resolved 3D ion implantation, in which the topography is suppressed, making these architectures ideal candidates for magnetism-controlled optics. We produce these structures using a novel processing technique employing Fe^+ implantation in continuous Pd thin films [6], through a pre‐patterned mask produced by EBL, yielding flat nano-magnetic array architectures.

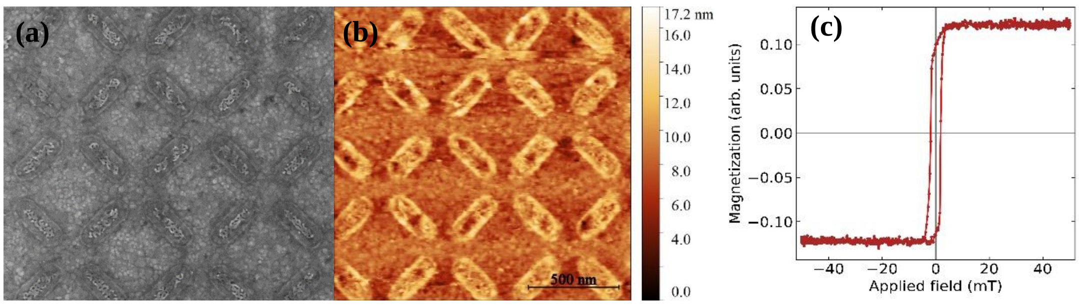

Figure 1: (a) SEM and (b) AFM images of implanted nanostructures. The structures are slightly swollen due to the Fe^+ implantation. (c) Hysteresis loop of the continuous implanted film without mask.

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Nonrelativistic THz emission and antisymmetric planar Hall effect in RuO_2(101) films

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RuO_2 is a captivating model material within the emerging field of altermagnetism, showcasing various intriguing phenomena, including strain-stabilized superconductivity, the crystal Hall effect, and spin splitting effects. In this contribution, we report two novel physical properties of this material.

Firstly, we present the observation of strong THz emission in the Pt/ RuO_2(101) bilayer system[1]. This THz emission involves a nonmagnetic mechanism that directly converts laser-excited high-density longitudinal charge currents into transverse ones, resulting in efficient terahertz-wave generation without the need for external fields. This mechanism differs from the inversed Hall effect observed in ordinary heavy metal/FM metal bilayer systems. The generation process is initiated by the super-diffusive charge current injected from the adjacency of an optically excited metal thin film. This current is then deflected from the longitudinally injected direction to the transverse direction by the anisotropic electrical conductivity of RuO_2.

Secondly, we report an unconventional antisymmetric planar Hall effect (APHE) observed under a magnetic field lying inside the plane spanned by the current and Hall electric field in RuO_2(101) films[2]. This APHE exhibits linearity to the in-plane field, unlike conventional Hall effects that are proportional to the perpendicular component of the applied field or magnetization. It also sharply contrasts with the well-known planar Hall effect, even under in-plane magnetic fields. Through a comprehensive study of its dependence on magnetic field direction, electric field direction, and temperature, we unequivocally demonstrate that the Lorentz force is the dominant mechanism behind the APHE. This conclusion is further substantiated by first-principles calculations, which quantitatively reproduce the measured Hall resistivity in experiments.

It is worth noting that these two novel phenomena in RuO_2(101) can also be observed in IrO_2(101) films with the same rutile oxide structure. Since IrO_2 is non-magnetic, the observed phenomena in RuO_2(101) should not be directly connected with the antiferromagnetism in RuO_2. Despite the lack of connection with the spin-splitting effect in RuO_2, our discovery of APHE and THz emission unveils new novel physical properties of this high-profile material.

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Quantum materials under the effect of dimensionality and disorder

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Here, we discuss an investigation of exotic quantum states in $FeGa_3$ under the presence of a delicate inclusion of Fe-antisite disorder, i.e., Fe_xGa_{3-x}. Energy Dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) determine the amount of Fe disorder and its atomic position at only one Ga site [1]. Mossbauer spectroscopy (MS) down to 1.5 K and magnetic field up to 14 T confirm the Fe antisite disorder, which influences the formation of in-gap states with electronic correlations and magnetic order below $T_m \sim 50$ K.

In addition, our electrical transport, magnetization, specific heat and XRD under simultaneous extreme conditions - very low temperature (T), very high pressures (up to 30 GPa) and intense magnetic fields (17 T) - reveal a non-canonical phase diagram for a quantum critical material, i.e., pressure reduces the in-gap states of the semiconducting ground state whilst strengths magnetic orders with distinct type of electron localization. Very interesting, such exotic electronic and magnetic ground states very close to a metal-insulator transition can be associated with the lowering of the crystal symmetry, the latest also scrutinized when our compound reaches small dimensionality as thin films or nanoparticles.

Our findings open new routes to understand the intriguing metallization and magnetism of strongly correlated electron systems [2] as well as to provide the benchmark for the realization of quantum materials under the presence of intrinsic but unavoidable disorder.

J. L. J, C. K. R., A. F. R. and V. M. acknowledge JP FAPESP 2018/08845-3, CNPq 31005/2021-6 and JP FAPESP 2018/19420-3. We acknowledge M.C.A. Fantini and N. Velisavljevic for the access to the LCr-IFUSP and the Advanced Photon Source (APS), Argonne National Laboratory, respectively.

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Co/Ni synthetic antiferromagnets heterostructures on polymer tapes: towards sustainable spintronics

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Synthetic antiferromagnets with perpendicular magnetic anisotropy (PMA-SAFs) have caught big interests for both conventional and advanced spin-based applications. Although great progress of PMA-SAF spintronic devices on rigid substrates has been achieved, only few examples on flexible thin film heterostructures, all containing platinum group metals (PGMs), are reported in the literature [1-2]. In this regard, Co/Ni system can offer additional advantages for the development of advanced spin-based devices. Moreover, decreasing the content of critical PGM elements is responsible for relieving the demand for strategic raw materials and reduce the environmental impact of related technologies, thus contributing to the transition towards a more sustainable future [3].

In this work [4], flexible Co/Ni-based PMA-SAFs and GMR spin-valves (SVs) containing a SAF reference electrode and a Co/Ni free layer were deposited on flexible polyethylene naphthalate tapes with different combinations of buffer (BL) and capping (CL) layers (i.e., Pt, Pd and Cu/Ta). High quality SAFs with a fully compensated AF region and SVs with a sizeable GMR ratio have been obtained in all cases. However, due to the different interdiffusion mechanisms occurring at the interface between the metallic layers, we demonstrated that while PGMs allow obtaining the best results when used as BL, Cu is the best choice as CL to optimize the properties of the stacks. The results thus indicate that complex Co/Ni-based heterostructures with reduced content of PGMs can be deposited on flexible tapes, allowing the development of novel shapeable and sustainable spintronic devices.

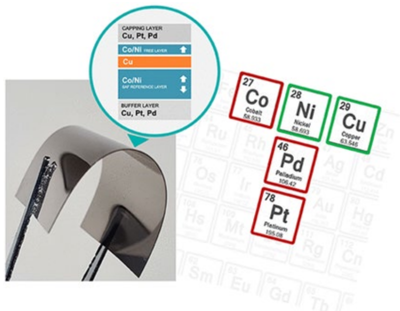

Figure 1: Fig. 1 Photograph and sketch of a flexible Co/Ni-based GMR spin valve consisting of a synthetic antiferromagnet reference electrode (SAF-RL) and a free layer (FL) separated by a Cu spacer.

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Atomically sharp domain walls in antiferromagnetic CuMnAs

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High quality thin films of tetragonal CuMnAs [1] grown by molecular beam epitaxy, were recently implemented in novel Spintronic devices. These rely on different phenomena, as are for example Néel vector reorientation via spin-orbit coupling [2] or thermal Quenching into high resistivity states [3].

We will present the results of our transmission electron microscopy measurements of the magnetic structure of epitaxial CuMnAs thin films on the atomic scale to demonstrate the existence of atomically sharp antiferromagnetic domain walls [4]. These results do not only help us explain the physical mechanisms behind interesting functionalities of CuMnAs devices [5], but also to get a better understanding of the crystalline/magnetic structure interplay in antiferromagnets. We will conclude by showing, that some of the intriguing phenomena previously observed only in CuMnAs is of a more universal origin and can be measured also in other materials with similar structure.

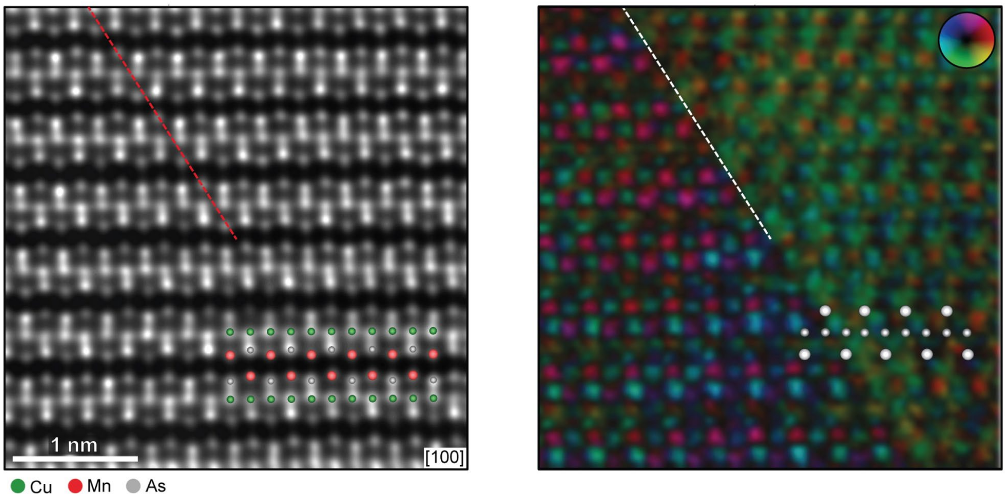

Figure: HAADF scanning electron transmission microscopy image (left) showing pristine crystal structure of CuMnAs. And a corresponding DPC scanning electron transmission microscopy image (right), where the color wheel reflects deflection of the electron beam. The abrupt difference in deflection (highlighted by the dashed line) is attributed to presence of an atomically sharp magnetic domain wall.

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Spin-polarized electron transport in single crystalline iron as function of temperature

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Although central for spintronics, the interplay between magnetism and transport in transition metal ferromagnets remains incompletely understood. In particular, the finite temperature resistivity of elemental Fe, Co, Ni could only be modelled partially from first principles.[1] In this communication, we address experimentally this interplay in a model system, using the recently developed technique of current-induced spin-wave Doppler shift [2] and following the degree of spin-polarization of electrical current as a function of temperature in a single crystalline iron film.

Figure (a) shows the spin wave device consisting of two inductive antennas integrated on a 14-µm-wide strip etched from a 21 nm Fe (001) film grown on a $MgAl_2O_4$ substrate. Following precisely the frequencies of counterpropagating spin waves, we extract the degree of spin-polarization of an electrical current injected along the strip.[2] This is found to increase from 75% up to 85% when cooling the sample from room temperature down to 5K [Fig. (b)]. This observation contradicts early considerations, which, based only on its global density of states, predicted a weak spin polarization for iron.[3] Instead, we believe majority electrons are much less affected than minority ones by the different scattering processes at play. Combining our polarization estimates with resistivity measurements conducted as function of temperature and high magnetic field,[4] we propose at a simple picture disentangling these different electron scattering processes [film surfaces, phonons and thermal magnons, Fig (c)].

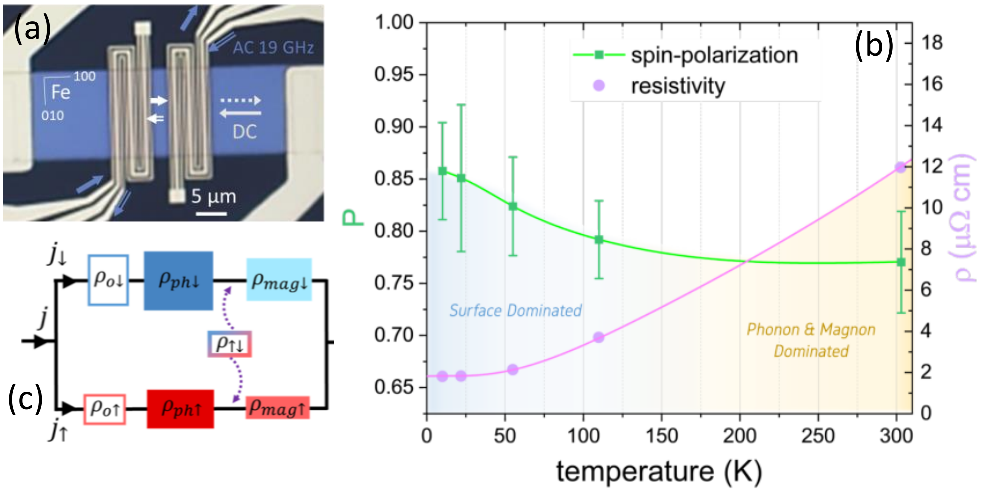

Figure. (a) Microscope picture of the device for current-induced Doppler shift measurement. (b) Temperature dependence of degree of spin-polarization of the current and resistivity in a 21 nm thick Fe (001) film. (c) Corresponding two-current resistor model.

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Tailoring magnetic anisotropy and domain wall chirality of Co/Ni bilayers by plasma oxidation

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Currently, the oxidation process is widely used to tailor the magnetic properties of ferromagnetic and ferrimagnetic layered films [1, 2]. Here, we focus on plasma oxidation (PO) because its ease of use, low-cost, and is a widespread technique in industrial applications. It can be performed on a large scale using commercially available tools. We will show that it might serve as an efficient approach to tailor magnetic properties [e.g., perpendicular magnetic anisotropy (PMA), exchange bias coupling (EBC), and Dzyaloshinskii-Moriya interaction (DMI)] and that it may constitute an improvement over other magnetic patterning methods.

Co/Ni layered systems are known for their low Gilbert damping and high spin polarization together with tuneable PMA by changing the layers' thicknesses [3]. Moreover, for this bilayer, it was found that the value and sign of DMI can be tuned by the chemisorption of oxygen on Ni [4]. Therefore, we investigate the influence of PO on magnetic properties of such a system. We demonstrate that PMA can be tailored not only by changing the thicknesses of Co and Ni layers, but also by controlling the PO time [5,6]. This process supports the formation of NiO at the expense of metallic Ni. This means that anisotropy changes are attributed not only to the reduction of metallic Ni layer thickness but also to the presence of EBC between antiferromagnetic (NiO) and ferromagnetic (Co/Ni) sublayers. This enhances the surface contribution to the effective anisotropy, favoring the perpendicular orientation of the Co/Ni [6]. Additionally, the presence of a NiO layer induces DMI, which stabilizes right-handed chirality in domain walls, similar to what was found for the Au/Co/NiO layered system [7].

As plasma oxidation can be performed locally, it allows the fabrication of 2D structures with different combinations of magnetic properties in the areas modified by plasma oxidation and in the areas protected against oxidation [6]. All these results show that Co/Ni systems subjected to plasma oxidation offer a wide spectrum of properties important for spintronics and magnonics applications.

Acknowledgments: This work was supported by the National Science Centre, Poland under OPUS 17 funding (Grant No. 2019/33/B/ST5/02013).

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Hydrogen absorption induced switching of the easy axis in Pt/Co/Pt

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Pt/Co/Pt heterostructures with perpendicular magnetic anisotropy (PMA) are traditionally used for magnetic recording to achieve high magnetic data storage density. PMA can be tuned by e.g. thin film thickness, strain, ion bombardment or temperature. Recently, it has been shown that the absorption of hydrogen in the heavy metal modifies the interfacial spin-orbit coupling and hence reduces the PMA [1, 2, 3]. As a result, magnetic hydrogen sensing can be performed, which was studied in an all-solid-state device and achieves in a Co/GdO$_x$ thin film system reversible and non-destructive toggling of the easy axis of magnetization between in-plane (IP) and out-of-plane (OOP) orientation at room temperature. [4]

Polarized neutron reflectivity is an effective tool for studying the hydrogen uptake and its impact on the magnetic properties in PMA systems. [2, 5] Recently, resonance enhanced polarized neutron reflectometry (RNR) has proven to be a quantitative method for the determination of the hydrogen concentration with high time resolution. [Guas22]

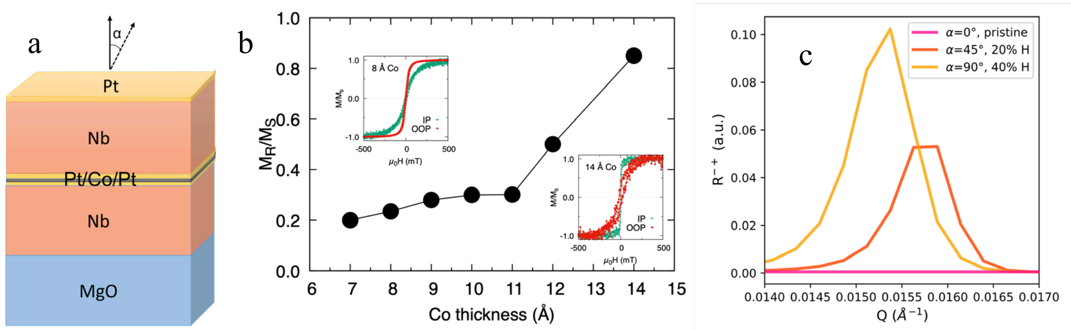

Figure 1: a. Sketch of sample and definition of the angle α for Co magnetization direction; b. Change of the in-plane squareness versus Co thickness obtained from SQUID magnetometry; c. PNR simulation around resonance position for different magnetization orientations revealing an increase of the in-plane magnetization with hydrogen concentration.

In this contribution we will study by RNR the impact of hydrogen uptake on the spin reorientation transition in polycrystalline Pt/Co/Pt trilayers sandwiched by 25 nm Nb layers on MgO(001) substrates fabricated by molecular beam epitaxy. Similar to the thickness driven spin-reorientation the easy axis of magnetization switches in-plane with hydrogen uptake. The applicability of the Pt/Co/Pt trilayers as sensors will be discussed.

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Spatially confined magnetic shape-memory Heuslers: implications for nanoscale devices

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Magnetic shape-memory (MSM) Heusler compounds are among the most important classes of materials for multiple-stimuli actuation and multicalorics, showing in addition promising multifunctional properties for energy harvesting, biomedicine, and spintronics. This multifunctionality stems from a reversible martensitic phase transformation (MT). Recently, successful epitaxial growth of these materials on silicon substrates using $SrTiO_3$ buffer layer has paved the way for integrating MSM Heuslers into micro/nanoelectronics and micro/nanomachining technology based on silicon [1]. However, for exploiting the material toward such small-scale applications, it is crucial to gain comprehensive knowledge about the key aspects of the material properties (e.g. MT) as a function of size.

In spite of recent advances in this topic regarding the size effects [2-5], the knowledge about the MT as a function of the size reduction specifically in the submicron scale is limited to the superelastic and thermomechanical characteristics of the material [6-8].

Therefore in this study, we aim to bridge this knowledge gap by systematically investigating the behavior of MSM Heusler systems upon micro/nanoscale confinement. We select and customize a top-down approach by patterning arrays of submicron epitaxial Ni-Mn-Ga structures with lateral sizes down to ~70 nm, using a Cr hard mask on MgO(001) substrate. The structures include straight stripes, radial stripes, squares and triangles. The martensitic transformation temperature, sharpness of the transition, thermal hysteresis and magnetic characteristics of the material are investigated as a function of the lateral size. With the aid of transmission electron microscopy techniques including Geometric Phase Analysis algorithm, as well as quantitative theoretical analysis of stress effects on the transformation, we evaluate the martensitic transformation of Ni-Mn-Ga starting from continuous films and down to sub-micron patterns. We show that the size-dependent internal stress relaxation plays a primary role in broadening the martensitic transformation of the material, reducing thermal hysteresis, and pushing the transformation toward higher temperatures. These findings highlight the importance of stress considerations upon incorporation of MSM Heusler materials into nanoscale functional devices.

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Mechanisms governing weak Dzyaloshinskii-Moriya interaction in a heavy metal/ferromagnet/oxide system

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Skyrmions are highly promising for developing novel applications such as racetrack memories or neuromorphic computing [1]. Ultrathin heavy metal/ferromagnet/metal oxide heterostructures with perpendicular magnetic anisotropy have been of particular interest in this context since they enable to locally invert the direction of motion of skyrmions induced by an electrical current, with a gate voltage, adding a new degree of freedom [2]. However, to exploit their potential and individually control skyrmions, a global understanding of the material system as well as the interfacial mechanisms determining their stability are essential. One key ingredient, characterizing a skyrmion as a chiral circular magnetic domain, is the antisymmetric exchange interaction, called Dzyaloshinskii-Moriya Interaction (DMI) [3]. Here, we present a combined experimental and *ab-initio* study on DMI in a Ta/FeCoB/TaO_x system showing weak DMI amplitude. Using chirality dependent domain wall motion, we experimentally found that the DMI sign varies with both the FeCoB thickness and the change in the oxidation state at the FeCoB/Ta(Ox) interface (Figure a, b). Using a simplified Fe/TaO_x system, our *ab-initio* calculations (Figure c) predict equivalent DMI sign changes. This combined *ab-initio* and experimental study paves the way for a deeper understanding of the mechanisms at the origin of interfacial DMI.

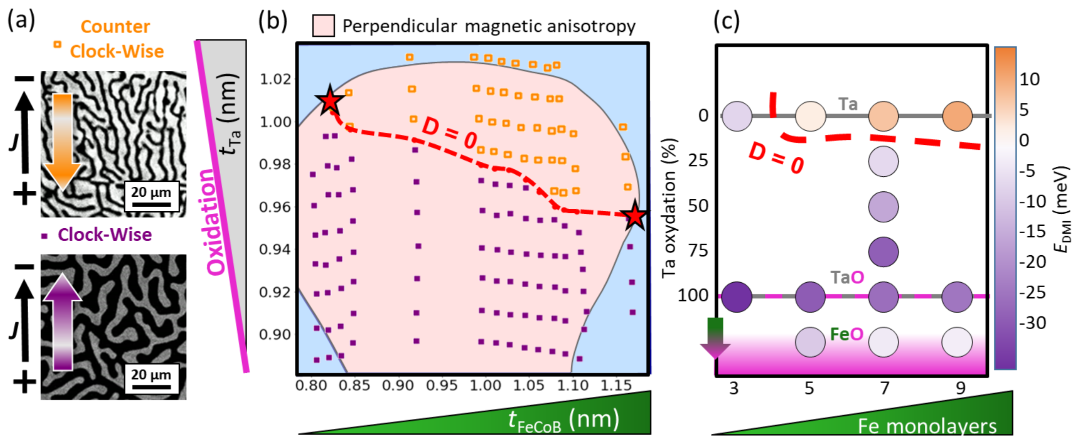

Figure. Determination of DMI sign by current induced motion of domain walls using magnetooptical Kerr effect microscopy (a), as a function of FeCoB thickness and FeCoB/TaO_x oxidation state (b). (c) *ab-initio* calculations of the DMI energy from a non-oxidized Fe/Ta to an optimally oxidized Fe/TaO and a FeO/TaO interface (top to bottom) and for increasing Fe monolayers (left to right).

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Homochiral antiferromagnetic merons, antimerons and bimerons realized in synthetic antiferromagnets

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Meronic spin structures have so far only been observed in native antiferromagnets [1] where they are difficult to observe and manipulate. A more flexible platform to explore and manipulate both static and dynamic properties of such in-plane topological solitons are synthetic antiferromagnets (SyAFM) [2], which combine the benefits of both FM and AFM scenarios: negligible stray fields, ultrafast spin dynamics, and detection of the absolute direction of the Néel order via imaging techniques that are suited for FM layers.

The stabilization of merons in an easy-plane-anisotropy thin-film system is primarily determined by the competition between the interfacial DMI (iDMI), the perpendicular magnetic anisotropy (PMA), and the demagnetizing field. Our micromagnetic model and the simulations show that the vanishing demagnetizing field in the easy-plane SyAFM multilayer reduces the iDMI required to stabilize (anti)merons significantly and these spin textures can be stabilized in such systems even at iDMI values one order of magnitude lower than for of a conventional single FM system [3].

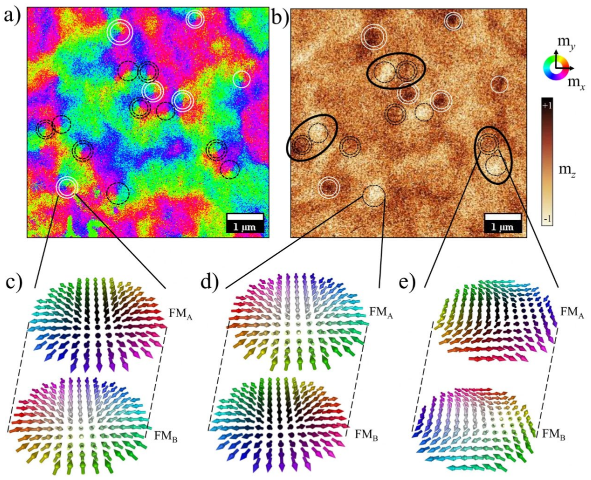

Figure 1: Combined SEMPA a) and MFM b) datasets from the very same area on the multilayer surface yielding the full local 3D magnetization vector [3]. They allow to unambiguously identify the spin structures of merons with different helicities and topological charges, as sketched in panels c) and d) and antimerons in e) for the two antiferromagnetically coupled magnetic sublayer stacks. Bimerons are marked by ellipses on panel b).

We have optimized multilayer SyAFM stacks containing two different heavy metals Pt and Ir with opposite signs of DMI at the FM interface to break inversion symmetry and generate a finite DMI. The thickness of Ir has been optimized for the first AFM coupling maximum between the FM layers. By exploiting the high surface sensitivity of in-plane sensitive scanning electron microscopy with polarization analysis (SEMPA) and combining it with the out-of-plane sensitivity of magnetic force microscopy (MFM), we obtain access to the full Néel vector orientation of the solitons. Fig. 1) shows such images from a SyAFM stack with 95% magnetic compensation, together with a topological analysis of the observed meronic spin structures.

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Three-dimensional skyrmionic cocoons in aperiodic magnetic multilayers

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Beyond the large number of studies on 2D topological textures such as magnetic skyrmions, a new interest has surged for more complex magnetic quasi-particles that display variations over the thickness, i.e., three-dimensional (3D) objects, leading to the discovery of new categories of 3D topological textures [1] in magnetic multilayers.

In this work, we show how by engineering Pt/Co/Al based multilayers with variable Co thickness, we observe the signature of new three-dimensional spin textures, called skyrmionic cocoons [4] that are only present in a fraction of the magnetic layers. Interestingly, these 3D cocoons can coexist with more standard 'tubular' skyrmions going through all the multilayer as evidenced by the existence of two very different contrasts in the magnetic force microscopy (MFM) images recorded at room temperature that can be easily correlated with the corresponding micromagnetic simulations (See Fig. 1). One major shortcoming of studying 3D textures is the difficulty to access information about the bulk magnetization. To this end, we also performed magneto-transport measurements as well as X-ray measurements at various synchrotrons. In Fig. 1c, an image acquired by holography, a transmission technique, clearly shows different contrasts that thus corresponds to objects with various vertical extension. Moreover, we have also obtained a reconstruction of the magnetization, measured with X-ray laminography evidencing the different magnetic textures in our aperiodic multilayers. Their coexistence and the discovery of a novel magnetic texture are particularly interesting as they

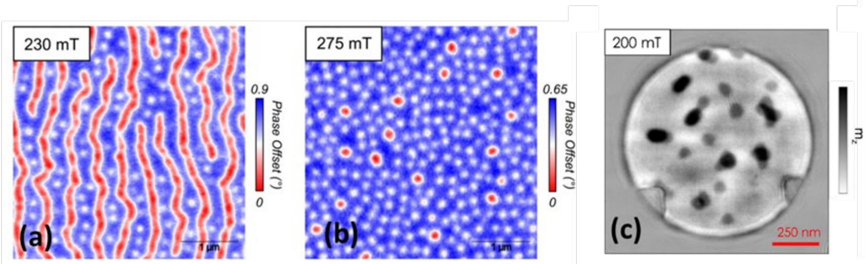

Figure 1 (a-b) experimental MFM phase maps displaying two types of textures (two different contrasts). (c) X-ray Fourier transform holography, a transmission technique, showing isolated cocoons (gray dots) and paired ones (black dots)

can open new paths for three-dimensional spintronics.

Financial supports from ANR-20-CE42-0012-01(MEDYNA), ANR/DFG (Topo3D), France 2030 under PEPR SPIN ANR-22-EXSP 0002 (CHIREX) and EU HORIZON-CL4-2023-DIGITAL-EMERGING (SkyANN; 101135729) are acknowledged.

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Investigation of synthetic antiferromagnets with interlayer chiral interactions using X-ray magnetic techniques

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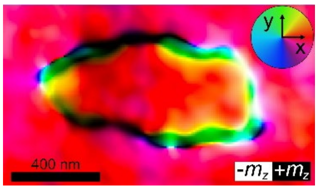
The theoretical prediction and experimental discovery of the interlayer Dzyaloshinskii–Moriya interaction (IL-DMI) in multilayer thin film heterostructures [1-3] opens new opportunities in spintronics, from field-free spin-orbit switching to the stabilization of 3D chiral spin textures. In this contribution, we present experimental investigation of synthetic antiferromagnets (SAFs) with IL-DMI using XMCD-based photoelectron microscopy (PEEM) and X-ray resonant magnetic scattering (XRMS). The SAFs investigated are of T-type, *i.e.* they are formed by two ferromagnetic layers separated by a metallic spacer, where the different proximity of both layers to the spin reorientation transition results in one being in-plane, and the other out-of-plane. We have previously shown how these T-SAFs present chiral exchange bias, a phenomenon understood to be caused by IL-DMI [2].



XMCD-PEEM vector reconstruction of the magnetization of a 360° domain wall ring

Here, we demagnetize the in-plane layer of T-SAFs using alternating magnetic fields, in combination with an offset field which partially or totally compensates for the chiral exchange bias value. We find that the domain structure and net vector chirality of the in-plane component is highly dependent on the degree of demagnetization of the layer, leading to the formation of either 360° domain wall rings [4], or spin states with well-defined overall scalar spin chirality. Using micromagnetic and atomistic simulations, we discuss these experimental findings, determining under which conditions IL-DMI can be understood as a net effective field acting on each layer, and when a more complex microscopic picture of the effect is needed. Additionally, we will discuss the methodology employed for vector tomographic reconstruction of the magnetization via XMCD-PEEM, where a systematic study has been performed to determine the optimal experimental conditions for accurate 3D reconstruction of the magnetization vector [5].

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Hysteresis-free voltage creation/annihilation of magnetic skyrmions

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Magnetic skyrmions, which exhibit Brownian motion in solids, are good candidate as information carriers in devices such as Brownian computing [1]. Voltage control of skyrmions is essential for the ultralow power consumption of such devices. Recently, in the case of skyrmion systems, voltage control of gate operation [2] and Dzyaloshinskii Moriya interactions (DMI) [3] have been reported. However, these voltage effects were attributable to a proton pump and redox reactions, and they are not suitable for high-speed devices. In this study, we aim to observe hysteresis free voltage effects on the density of skyrmions.

We deposited films with following the stacking structure Si/SiO_2 sub.| Ta(5) | Co-Fe-B(1.05) | Pt(0.14) | MgO(1.5) | SiO_2(3) (described in nm) and fabricated the devices with applying electrical field in out-of-plane direction. We attempted to prevent ion migration by inserting Pt between Co-Fe-B and MgO. The MOKE images under different bias voltages are illustrated in Fig. 1. As evident, the number of skyrmions increased or decreased with the application of negative or positive voltages, respectively. We observed the creation and annihilation of skyrmions according to the sign of the applied voltage. Moreover, it returned to normal when the voltage returned to 0 V. In this voltage sweep measurement, the sample exhibited only as small hysteresis within the statistical error. Thus, the number of skyrmions was stably controlled by the voltage, and a hysteresis-free response was confirmed. However, no voltage dependence of the hysteresis loops in MOKE signals corresponding to the *M*–*H* curve was observed as shown in Fig. 2. This result implied the voltage control of only the DMI. This work was supported by JSPS KAKENHI Grant Number JP20H05666, 23KJ1477, Japan and JST CREST Grant Number JPMJCR20C1, and MEXT Initiative to Establish Next generation Novel Integrated Circuits Centers (X-NICS) Grant Number JPJ011438.

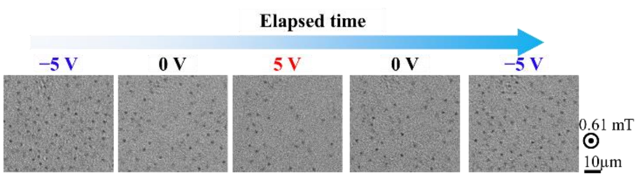

Figure 1: MOKE images during sweeping the voltage from -5 V to 5 V at 423 K.

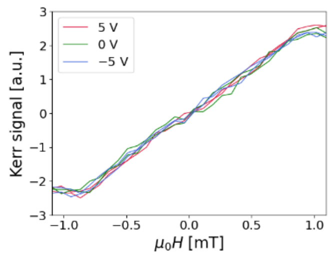

Figure 2: Voltage dependence of the Kerr hysteresis curve at 433 K.

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[3] C.E. Fillion *et al.*, Nat.Commun.**13** 5257 (2022)

Quantifying the topology of magnetic Skyrmions in three dimensions

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[c] Swiss Light Source, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
[d] Western Digital Research Center, Western Digital Corporation, San Jose CA 95119, USA
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The description of magnetic Skyrmions as 2D objects has provided an enormous insight into their properties, behavior, and functionality, specifically towards the exploration of magnetic Skyrmions in future spintronics applications. However, in real systems with a finite thickness larger than the magnetic exchange length, the details of the spin texture extending into the third dimension cannot be neglected. One cannot assume that a skyrmion extends into the third dimension simply as a rigid skyrmion tube as there is an additional dimension for evolution into a more complex 3D spin texture. Most importantly, advanced synthesis methods allow for a highly precise engineering of materials that extend into the third dimension, and therefore a fundamental understanding of the full 3D spin texture opens opportunities to explore and tailor 3D topological spintronic devices with enhanced functionalities that cannot be achieved in two dimensions. Spin textures including Skyrmion tubes [1], [2], Hopfions [3], torons, cocoons, and vortex rings [4] as well as ferroelectric polar skyrmions [5], and artificially designed magnetic nanostructures, such as twisted wires, tetrapods etc. are among such 3D topological building blocks that are currently receiving significant interest [6],[7].

Using soft x-ray laminography we have reconstructed with about 20 nm spatial (voxel) size the full three-dimensional spin texture of a Skyrmion in an 800 nm diameter and 95 nm thin disk patterned from a 30×[Ir/Co/Pt] multilayered film structure [8]. A quantitative analysis finds that the evolution of the radial profile of the topological skyrmion number is non-uniform across the thickness of the disk. Estimates of the local micromagnetic energy densities suggest that the changes in topological profile are related to non-uniform competing energetic interactions. Theoretical calculations and micromagnetic simulations are consistent with the experimental findings.

Our results provide the foundation for nanoscale magnetic metrology for future tailored spintronics devices using topology as a design parameter.

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Revealing the three-dimensional nature of the field-driven movement of magnetic topological defects

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Understanding the processes of creation, propagation, and annihilation of topological defects is key to gaining control over the different processes they mediate [1]. In magnetism for instance, magnetic switching is mediated by domain wall motion [2] while vortex core reversal is driven by Bloch point singularities [3]. Here, we focus on magnetic dislocations in stripe domains and their role in the field-driven continuous rotation of the stripes. By harnessing both 2D and 3D magnetic imaging, specifically combining 3D soft X-ray magnetic vectorial imaging [4] with the application of in situ magnetic fields, we track and characterise not only the motion of these defects, but also how their underlying 3D configuration influcences this behaviour. [5]. These advances establish the necessary capabilities to study the behavior of topological textures in 3D, opening the door to insights

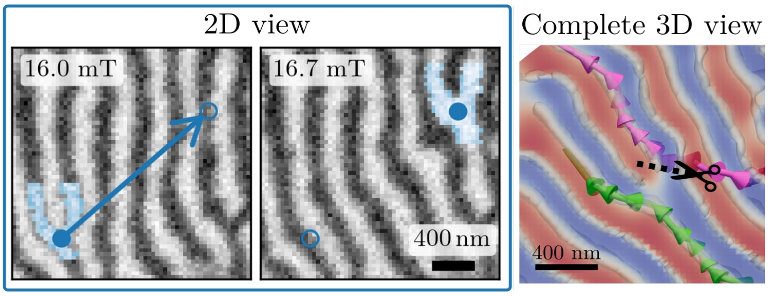

Figure 1: The movement of dislocations driven by an external magnetic field as seen by 2D (left) and 3D imaging (right): the inner magnetic structure revealed by 3D imaging, highlighted in pink and green, is involved in the mechanism for the movement of the dislocations.

into the field-driven behavior of buried three-dimensional magnetic textures.

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Rare-earth Spintronics: from orbital-momentum polarization to the Dzyaloshinskii-Moriya Spin density

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Spintronics investigates the flow and interconversions of spin and charge degrees of freedom. While most spintronic systems rely on transition-metal atoms, such as Fe, Co, and Ni, rare earths (*e.g.,* Nd, Dy, Ho, and Tm) are gathering increasing attention due to their advantageous spin-orbit coupling and sizeable orbital momentum that induces or assists the perpendicular-magnetic anisotropy of magnetic insulators [1], voltage-control of magnetic anisotropies [2], spin-orbitronic devices [3], and magnon drift currents [4].

This talk starts reviewing recent advances in rare-earth-based spintronic materials and phenomena [1-6]. Then, we concentrate on the formation of an *orbital polarization* [5] and a non-collinear *Dzyaloshinskii-Moriya Spin-Density* (DMSD) [6] around RE impurities in metals. The orbital polarization is a charge current vortex in conduction electrons, and it may be viewed as the "orbital" equivalent to the RKKY spin density induced by a localized spin. On the other hand, we show that RE atoms create an anisotropic spin density, *i.e.,* a Dzyaloshinskii-Moriya Spin-Density, see Fig. 1, which is responsible for the anisotropic exchange in RE-containing materials and interfaces [6] and allows controlling the strength and symmetries of the anisotropic exchange by moving the RE magnetic moment. Finally, we extend the previous discussion to a dynamic localized orbital momentum, for which the spin and orbital polarizations induced in the metal become dynamic and come along with the emission of spin and orbital-angular momentum currents.

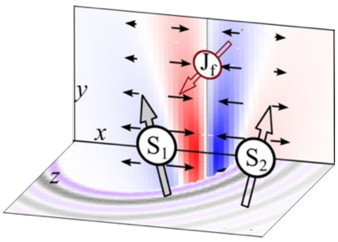

Figure 1. The Dzyaloshinskii-Moriya Spin Density (DM-SD). There is a conduction-electron spin density collinear to each atomic spin. In addition, the spin-orbit coupling of heavy atoms, such as rare earths, rotates these densities creating an anisotropic contribution, i.e., the DM-SD. The big arrows stand for atomic spins, while the small black arrows are the conduction-electron spin density, namely, the DM-SD.

Acknowledgments: We thank Fondecyt No. 11230120.

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Magnetic anisotropy in half-metallic $Co_2FeAl_xSi_{1-x}$ Heusler alloy thin films

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Due to its half-metallicity and high Curie temperature, Co-based Heusler alloys are promising materials for spintronic devices such as magnetic random-access memory (MRAM) and magnetic sensors. In such devices, magnetic anisotropy of Co-based Heusler alloys plays an important role in their performance. In this study, $Co_2FeAl_xSi_{1-x}$ Heusler alloy thin films were grown, and their magneto-crystalline anisotropy was systematically investigated.

50-nm thick $Co_2FeAl_xSi_{1-x}$ films were deposited on (001)-oriented MgO single crystalline substrate by co-sputtering method with Co_2FeAl and Co_2FeSi targets, and then annealed at 500˚C to improve their crystallinity. We have firstly investigated their crystalline properties by X-ray diffraction. It was found that above 80% of B2 ordering was observed in all the samples but $L2_1$ structure was detected only in the samples with x below 0.4, indicating that all the samples show half-metallicity. Next, in-plane ferromagnetic resonance (FMR) was performed to evaluate magneto-crystalline anisotropy of the samples.

Figure 1 (a) shows the angular dependence of the in-plane FMR resonance field for the $Co_2FeAl_xSi_{1-x}$ thin films. It is evident that the magnetic easy axis has changed from [100] to [110] with increase of x. To calculate magneto-crystalline anisotropy, we have performed the fitting with the function suggested by H. Suhl.[1] The red dots in Figure 1 (b) show first cubic magneto-crystalline anisotropy constant K_1 of the $Co_2FeAl_xSi_{1-x}$ thin films evaluated from in-plane FMR. The K_1 has changed from small positive to negative value crossing zero value at around $x = 0.3 – 0.4$. This behavior of K_1 agrees with that evaluated from magnetization curves measured by vibrating sample magnetometer (VSM) [shown as blue dots in Figure 1 (b)]. The smallest K_1 measured in this study was < 1000 erg/cc, which is the smallest value reported for Co-based Heusler alloy thin films.[2] In summary, $Co_2FeAl_xSi_{1-x}$ thin films with $x = 0.3 – 0.4$ possess both half-metallicity and small magneto-crystalline anisotropy constant K_1. This unique material is thus a good candidate for enhancing the performances of various spintronics devices like magnetic sensors.

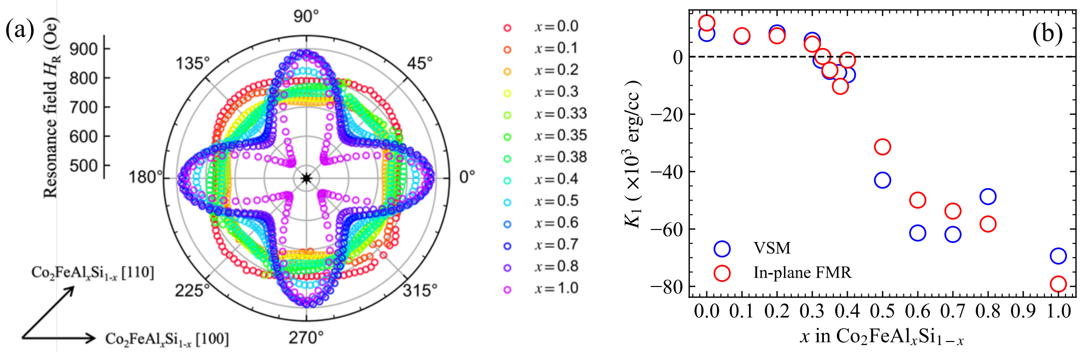

Figure 1 (a) the angular dependence of in-plane FMR resonance field for $Co_2FeAl_xSi_{1-x}$ thin films and (b) the first magneto-crystalline anisotropy K_1 evaluated by VSM (blue dots) and in-plane FMR (red dots).

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Exploring stack-structures for over 400% tunnel magnetoresistance in spin-valve-type CoFeB/MgO/CoFeB junctions

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Magnetic tunnel junctions (MTJs) are core elements in various spintronic applications, such as magnetoresistive random access memories (MRAMs) and neuromorphic computing devices. A large tunnel magnetoresistance (TMR) ratio is one of the key features of MTJs in these applications; however, its improvement has been stagnant for a long time. Recently, we have demonstrated a TMR ratio of 631% at room temperature (RT) using a single-crystal CoFe/MgO/CoFe MTJ structure [1], surpassing the previous record of 604% in 2008 [2]. This significant improvement was achieved by controlling the MgO barrier interface structure. In this study, we extended this single-crystal MTJ technology to practical CoFeB/MgO/CoFeB-type polycrystalline MTJs by introducing a high-throughput sputtering deposition apparatus with features such as automatic substrate transfer, automatic wedged layer formation system, and reflection high-energy electron diffraction (RHEED) acquisition.

In-plane magnetized MTJ stacks were deposited on thermally oxidized Si substrates by automated magnetron sputtering with a top-spin-valve structure consisting of a Ta/Ru buffer/CoFeB (4)/MgO (1.1)/CoFeB (t_{CFB})/CoFe (t_{CF})/Ru (1.3)/CoFe (3)/IrMn (8)/Ru cap (unit: nm). To optimize the thickness of each layer, wedged layers were formed in the *X* and *Y* directions by controlling a linear shutter. *In-situ* post-annealing was performed to tune the MgO barrier quality, and its crystallinity was monitored by RHEED system. The TMR ratio was characterized at RT by automated TMR measurement system after patterning into an MTJ area of 40 μm^2.

Figure 1 shows an example of the efficient screening by obtaining a TMR map against t_{CFB} (*X*-direction) and t_{CF} (*Y*-direction). Large TMR ratios above 340% are obtained over a wide area, but there is a sharp drop in values at two locations near the edges. This drop indicates a reduction in the degree of (001)-orientation of the top ferromagnetic layer. After further optimization of the deposition processes and thicknesses, a TMR ratio of up to 405% was achieved, which exceeds the reported value for exchange spin-valve type CoFeB/MgO/CoFeB MTJs (365% [3]). This work was partly supported by JSPS KAKENHI Nos. 21H01750 and 21H01397, and MEXT Program: Data Creation and Utilization-Type Material Research and Development Project Grant Number JPMXP1122715503.

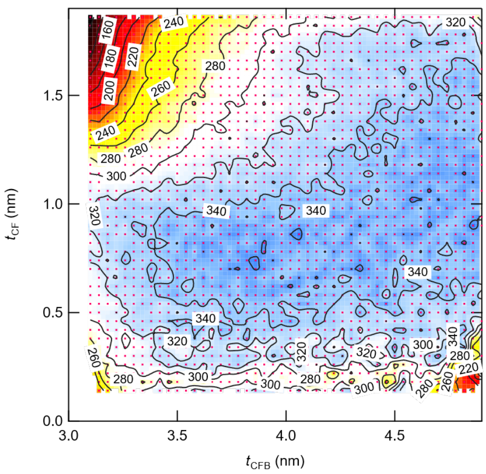

Figure 1: TMR ratio in percent of CoFeB/MgO/CoFeB (t_{CFB})/CoFe (t_{CF})/Ru/CoFe/IrMn top-spin-valve MTJs. Dots represent measured MTJ positions.

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Bayesian inference using nanomagnet arrays

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Artificial Spin Ice is the name given to a class of metamaterials that are used as models for frustrated systems. In these models, frustration is introduced through competing interactions in a mesoscopic-scale array of interacting particles. The flexibility to design interactions underwrites their use in studies of spin dynamics and ordering phenomena in low dimensions. Recent advances in fabrication now enable creation of complex two- and three-dimensional structures [1] and novel mechanisms for the control of magnetic states [2,3.] A new type of three-dimensional Artificial Spin Ice geometry is proposed in which a feedback scheme enables it to behave similarly to a proportional–integral–derivative controller (PID). The theoretical design principle is derived from a biologically plausible neuroscientific model. Cast in the form of nanomagnetic spin geometries that can be studied experimentally, the approach can be used to facilitate an understanding of how complex systems might be used for Bayesian filtering schemes.

A 'smart Artificial Spin Ice' designed using this principle [4] is shown to behave similarly to a PID as predicted by active inference theory developed for biology and neuroscience [5]. Moreover, we show how our nanomagnet system can, under certain circumstances, display a curious dependence on temperature resulting in complex nonlinear dynamics manifested as quasi-periodic oscillating magnetization processes.

This work is supported by the Natural Sciences and Engineering Research Council of Canada RG- 430 and the Canada Foundation for Innovation JELF.

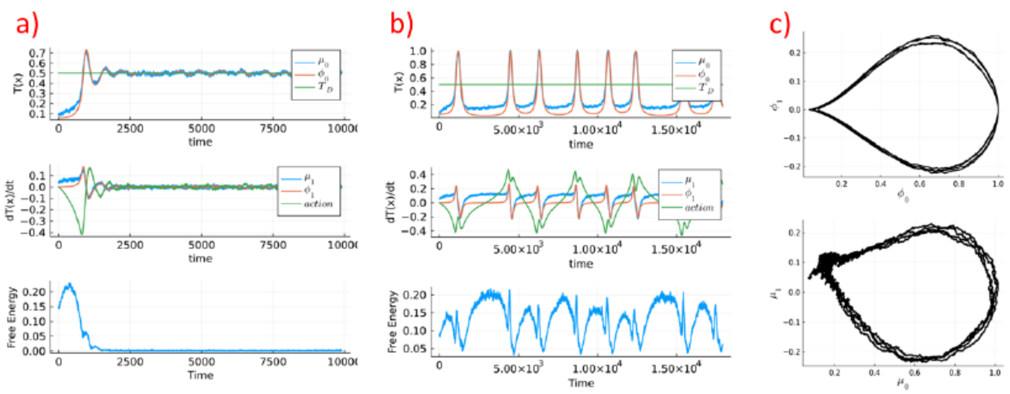

Figure: a)Sensory layer spins receive environment position and velocity information and hidden layer spin states drive the system towards a target velocity. b) & c) quasi-periodic oscillations appear in a narrow temperature range.

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Emergence of the Ferromagnetic-Glass Texture in Co layers hybridized with Molecules

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The interface between 3d ferromagnetic thin films and molecular layers is known to alter key ferromagnetic properties, such as magnetic anisotropy, magnetic moment etc. [1,2]. The effect is originated by the hybridization between the metal surface d orbitals and the p molecular orbitals. It induces significant modifications to the effective surface Spin-Orbit Coupling and hence to the Magneto-Crystalline anisotropy term [3].

In this work, we investigate the hybridization effects of fullerene C_{60} and Gallium-quinoline (Gaq_3) molecules on the magnetic properties of polycrystalline 5 nm thick Cobalt layers. MOKE and SQUID measurements showed a significant in-plane magnetic hardening of the cobalt layer: from 2 times at room temperature to a colossal two-fold enhancement at low temperatures (Fig 1a). Further, the investigations of minor loops (Fig 1b), revealed fully unusual magnetization dynamics with a clear deviation from the Rayleigh law [4]. This new physics is explained on the basis of a new 2D phenomenological micromagnetic model with an additional interfacial anisotropy term K_R characterized by a correlation length r_C. For $r_C \sim \Delta$ (domain wall length) K_R dominates over any present anisotropy in the FM layer, inducing and enlargement of the hysteresis loops, as experimentally observed. The system's ground state (zero net magnetization) is no more divided into domains but it is characterized by continuous, randomized directions of the magnetization vector (Fig 1c,d). We believe that this new Ferromagnetic Glass Texture (FGT) state arises from the competition of two magnetic length scales, such as r_C and magnetic exchange length and reflects a more general property for various collective effects in solid state physics.

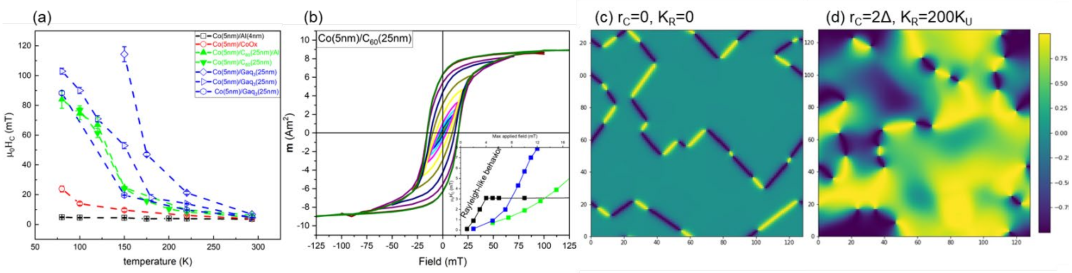

Fig. 1 (a) *Coercive fields vs temperature for Co interfaced with C_{60} and Gaq_3, compared with reference Co/Al and Co/CoOx systems. (b) Minor loops of a Co/C_{60} thin film at 150K, inset shows the minor coercivity as function of the maximum applied field for Co/C_{60}, Co/Gaq_3 and Co/Al. Micromagnetic simulation of the m_y component of the magnetization vector in the demagnetized state: (c) with no Random anisotropy term, (d) with a strong random term and $r_C=2\Delta$*

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Microscopic understanding of magnetoresistance in a chiral molecule-ferromagnet junction

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Chirality, defined as a pseudo-scalar that changes sign under mirror reflection, is characterized by the lack of mirror symmetry. Recently, numerous phenomena related to chirality-induced spin selectivity (CISS) have been reported in the field of physical chemistry [1, 2]. Particularly noteworthy among CISS-related phenomena are the manifestation of magnetoresistance in junctions involving chiral molecules and ferromagnetic electrode. However, within the linear response domain, the occurrence of magnetoresistance is theoretically prohibited. Nevertheless, experimental studies have reported exceptional very large magnetoresistance, surpassing those observed in commercially available spintronic devices, such as the CoFeB/MgO system. Consequently, a comprehensive and unified understandings of CISS-related phenomena remain elusive, posing a significant challenge to its practical application and further advancement in the field. In this study, we employed the prototypical chiral electrolyte, (1*S*)-(+)- or (1*R*)-(−)-camphor-10-sulfonic acid (*S*- or *R*-CSA) [3], alongside ferromagnetic CoPt electrodes, to perform time-resolved observation of magnetoresistance and discuss its microscopic origin [4].

Electric measurements were carried out using a custom-made electrochemical cell. The multilayer structure, comprising Ta (5 nm)/Pt (10 nm)/CoPt (8 nm)/Au was fabricated on a thermally oxidized silicon substrate. The multilayer films were then patterned into the electrodes suitable for electrochemical cell, employing conventional photolithography techniques. The electrolyte solution was composed of H_2O, chiral electrolyte (*S*- or *R*-CSA), and a supporting electrolyte (KCl). CSA was used at a concentration of 0.25 mM. The electrical measurements were carried out utilizing a two-terminal method. From the time-resolved magnetoresistance measurements, we find that the essence of CISS lies in the interlayer exchange coupling between chiral molecules and the ferromagnetic electrode. This is mediated by conduction electrons through the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction. The spontaneous spin polarization of chiral molecules plays a central role. This concept is consistent with recent observations of CISS-related phenomena occurring in the absence of a bias current in the system, suggesting a signature of the thermally driven spin polarization in chiral molecules [5, 6].

This work was partially supported by JSPS-KAKENHI (Nos. 22K18320, 22H00290, and 22H04964), JST-ASPIRE (No. JPMJAP2317), Spintronics Research Network of Japan (Spin-RNJ), and MEXT-Xnics (No. JPJ011438).

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Controlling domain propagation modes in square artificial spin ice

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Artificial spin ice (ASI) systems are arrays of single domain nanomagnets arranged in a periodic or aperiodic lattice that exhibit geometrical frustration, emergent magnetic monopoles, and collective magnetization dynamics [1]. Recently, ASI systems have moved beyond mimicking spin ice materials and emerged as a functional model system for neuromorphic computing [2]. In square ASI, magnetization reversal via an applied magnetic field leads to 1-d avalanches of switching [3], which is not desirable for practical application. Controlled and avalanche-free monopole propagation and magnetization reversal are still challenging in square ASI. In a recent work, our group has shown that by using the astroid clocking method one can achieve control over ferromagnetic domain growth in pinwheel ASI [4].

In this work, we explore different domain modes in square ASI via astroid clocking protocols and demonstrate controlled propagation of magnetic monopoles and ferromagnetic domains. Magneto-optical Kerr Microscopy is used for domain imaging. We find that the different modes of domain growth are dependent on the angle of the clocking field. Clocking angles close to 90° promote growth of Dirac strings whereas at wider angles we observed ferromagnetic domains.

Our experimental results are in excellent agreement with simulations of ASI magnetization reversal using the flatspin simulator. The system subjected to the clocking fields shows a stepwise domain propagation as opposed to conventional field sweeps which give rise to avalanche-like switching and the inevitable loss of encoded information. The newfound control over avalanche-free magnetic monopoles and ferromagnetic domain propagation in the square ASI holds promise for potential applications in data storage and information processing.

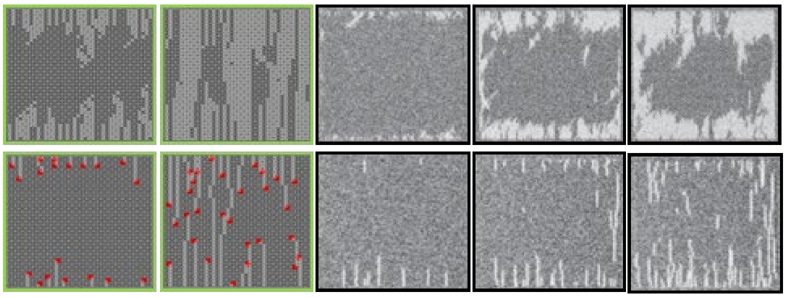

Figure 1: Simulation (green boxes) and MOKE (black boxes) images showcase different modes of propagation in square ASI system for different clocking field protocols. Top row: controlled ferromagnetic domain propagation. Bottom row: controlled and stepwise monopole propagation (red dot indicates monopole).

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Resonant soft x-ray studies of artificial spin ices containing defects of varying topological charge

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Artificial spin ices (ASIs) serve as model systems for collective magnetic behavior as well as platforms for unconventional computing and control of X-ray beams. [1], [2] Topological defects in ASIs[3] are expected to profoundly affect ASI's ground states, response to external fields, dynamics, and interactions with light. Resonant soft x-rays offer a versatile probe for these phenomena through x-ray magnetic circular-dichroism photoemission electron-microscopy (XMCD-PEEM), coherent x-ray scattering and photon correlation spectroscopy (XPCS), and new dichroic techniques based on x-ray orbital angular momentum (OAM).[4]

We present recent findings concerning permalloy, square ASIs with defects of varying topological charge as shown in Fig. 1. XMCD-PEEM confirms that even-charge defects yield single-domain antiferromagnetic (AF) grounds states while odd-charge defects introduce frustration with many nearly degenerate states containing superdomain walls. Both XMCD-PEEM and XPCS reveal that near-equilibirum fluctuations depend on topological charge. For even-charge defects, spin flips near edges and abrupt nuclation and annihiliation of superdomains are obsevered. For odd-charge defects, spin flips near the superdomain wall and superdomain wall motion are the dominant fluctuations. These structures also yield dynamic X-ray beams containing a superposition of multiple OAM states. Finally, simulations indicate topological defects significantly change the field-driven reversal process between saturated states of the square ASI. AF domains nucleate between the defect and the edges of the ASI leading to a configuration opposite that of the frustrated ground states. Near-UV magnetooptic Kerr effect (MOKE) measurements are underway to confirm these simulations.

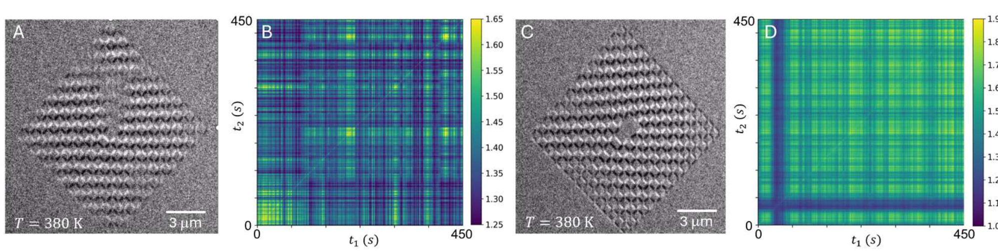

Figure 1: Square artificial spin ices are strongly influenced by the charge, $\mathbb{Z}$, of topological defects. **A** XMCD-PEEM image for $\mathbb{Z} = 1$ shows a large AF ordered region with a fluctuating superdomain wall. Fluctuations (grey regions) occur around the superdomain wall and through superdomain wall motion. **B** XPCS two-time correlation for $\mathbb{Z} = 1$ shows short intervals of strong correlation with frequent fluctuations. **C** Square ASI with $\mathbb{Z} = 2$ orders into a single domain AF ground state. **D** XPCS two-time correlation for $\mathbb{Z} = 2$ shows long periods with weak fluctuations interrupted by abrupt reconfigurations.

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Emergent spin–orbit induced phenomena in terahertz magnon dynamics in magnetic layered structures

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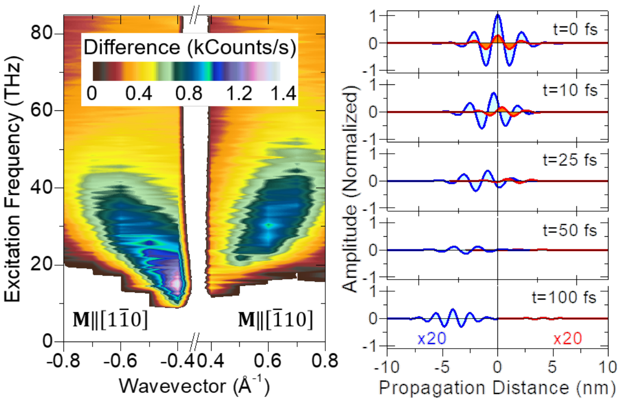
We will present our recent experimental results on the dynamics of terahertz (THz) magnons in layered magnetic structures, epitaxially grown on substrates with a large spin–orbit (SOC). The results were obtained by means of spin-polarized high-resolution electron energy-loss spectroscopy (SPHREELS), which provides a momentum-space representation of THz magnons over a wide range of momentum and frequency.

First, we will discuss how a careful investigation of THz magnon dynamics enables one to quantify the atomistic Dzyaloshinskii–Moriya interaction (DMI) in layered structures and resolve the complex pattern of atomistic DMI in such structures. We present the results of a model system, i.e., an epitaxial Co double layer grown on Ir(001). We report on the discovery of a chirality-inversion of the atomistic DMI, i.e., a sign change in the chirality index of DMI from negative to positive, when comparing the interaction between nearest neighbours to that between neighbours located at longer distances. The effect is in analogy to the change in the character of the Heisenberg exchange interaction from ferromagnetic to antiferromagnetic [1].

Second, we will introduce a novel mechanism, which leads to a giant nonreciprocity of ultrafast THz magnons in ferromagnetic films and multilayers with a large SOC. The mechanism is based on the competition between the exchange and spin–orbit scattering. During the scattering process, when electrons excite THz magnons, the two spin-dependent scattering processes, i.e. spin–orbit and exchange processes, compete with each other. On the one hand, SOC couples the spin to the crystallographic directions. On the other hand, in ferromagnets the time-reversal symmetry is naturally broken. These facts lead to a substantially different excitation cross-section of THz magnons propagating along opposite (but crystallographically equivalent) directions (see Fig. 1). We anticipate that the effect can be utilized to excite nonreciprocal or even unidirectional THz magnons in a large class of ultrathin films and nanostructures grown on substrates with a large SOC [2].

Fig. 1. (left) Frequency–momentum map of the excitation spectra recorded for the two opposite directions. The color scale represents the amplitude of coherently excited magnons. Data with the positive (negative) value of wavevector denote the propagation direction along the [110]- ([$\bar{1}\bar{1}$0]-) direction. (right) The evolution of the magnon wave packets with the momentum of 0.4 $Å^{-1}$ in real time and space. The blue (red) wave packet propagates along the [110]- ([$\bar{1}\bar{1}$0]-) direction [2].



Financial support by the DFG through grants ZA902/7-1 and ZA 902/8-1 is acknowledged.

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Element-specific FMR spectroscopy at high frequencies, detected with coherent extreme ultraviolet light

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X-ray detected ferromagnetic resonance (XFMR) spectroscopy provides a unique tool for metrology of magnetic thin films and devices, due to its ability to measure individually the ferromagnetic resonance of each element in a sample [1]. Until now, XFMR has generally been shown at frequencies below 12 GHz, and has been performed only at synchrotron sources. We present here a laboratory-scale instrument developed at NIST-Boulder that uses ultrafast, extreme ultraviolet (EUV) light to perform XFMR spectroscopy [2]. It uses an RF frequency comb generator to create high-order harmonics of a photodiode signal from the laser oscillator pulse train, and thereby generates a microwave excitation that is inherently synchronized to the EUV pulses with a timing jitter of 1.4 ps or better, even at frequencies exceeding 60 GHz.

We used this instrument to measure three samples on opaque Si substrates: permalloy (8.5 GHz), a Co-Fe alloy (17 GHz), and a Ni/TaOx/Fe multilayer (8.5 GHz). These measurements highlight the ability to perform high-frequency, element- and/or layer-resolved XFMR. The applicability to higher frequencies enables XFMR measurements of materials with high magnetic anisotropy, in addition to ferrimagnets, antiferromagnets, and high-wavevector spinwaves in nanodevices. In the future, we will be able to utilize the coherence of the source and combine this capability with dynamic, nanoscale, lensless imaging techniques such as ptychography and holography, and measure dynamics and transport in active devices.

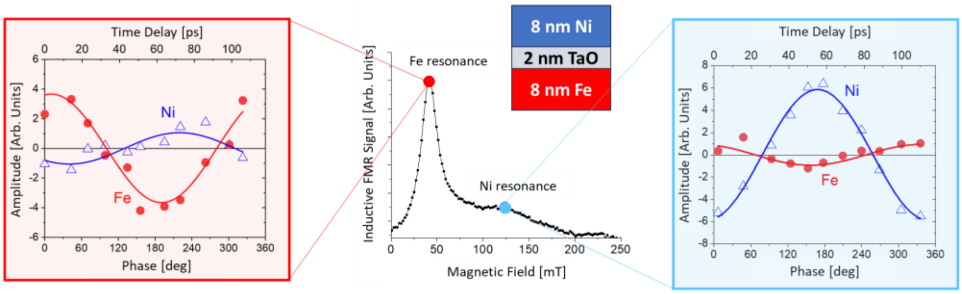

Figure 1: Element-resolved ferromagnetic resonance measured in an Fe/TaOx/Ni multilayer. On the left (right) are the time-dependent precession of each element, measured at the resonance field of iron (nickel) in this sample. An inductive FMR measurement of this sample is shown in black in the middle plot. Notably, the measured precession angle of each element is greatest at its resonance field.

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Tunning the antiferromagnetic phase in epitaxial thin films of $La_{1-x}Sr_xMnO_3$ prepared by polymer-assisted deposition

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Apart from its intrinsic fast dynamics in the THz range, antiferromagnetic (AF) materials also poses a series of properties such as stability and immunity against external magnetic noise, spin angular momentum conservation, and absence of stray fields that underscore the potential of AF in advancing spintronics for various technological applications, ranging from high-speed data processing to fundamental improvements in information storage and device performance and low power consumption. On the other hand, complex oxides offer a remarkable interplay between electronic, orbital, structural, and magnetic degrees of freedom that drives to a wide diversity of structural, magnetic, and transport phases that compete or even coexist inducing large responses to external stimuli. In particular, the $La_{1-x}Sr_xMnO_3$ system exhibits a complex phase diagram including AF ordering for x~1/2. Our interest in this work was obtaining good quality thin films of $La_{1-x}Sr_xMnO_3$ manganite with AF ordering for which the versatility of the PAD technique to control the stoichiometry is fundamental. Thin films of the $La_{1-x}Sr_xMnO_3$ system, with compositions ranging from 0.5 to 0.65, were prepared via the polymer-assisted deposition method on $SrTiO_3$ (100) substrates. Our main aim was to stabilize the A-type AF phase associated with x~ 1/2. However, the electronic and magnetic characteristics of the samples, featuring varying levels of La substituted with Sr, deviate from the expected behavior based on the bulk phase diagram. Through X-ray absorption spectroscopy, we reveal that the effective Mn^{3+}:Mn^{4+} ratio of 0.5:0.5 is actually achieved in the sample with x= 0.65, indicating an alternative charge compensation mechanism. Utilizing high oxygen pressure annealing techniques, we demonstrate that oxygen vacancies, formed to alleviate epitaxial structural strain, contribute to partial charge compensation and the observed deviations from the bulk phase diagram.

Switching of Néel vector in hematite thin films by exchange coupling with cobalt layers

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Antiferromagnetic (AFM) films are essential components of spintronic devices because of their unique properties, such as robustness against magnetic field perturbations, fast spin dynamics, and lack of stray fields. However, the absence of a net magnetic moment in AFM materials is a challenge for electrical reading of their magnetic state. The exception is hematite (α-Fe_2O_3), which is weakly ferromagnetic (FM) at room temperature (RT). This allows switching of the Néel vector in ultrathin epitaxial hematite films covered with a heavy metal layer, e.g. platinum by spin-orbit torque [1]. The subject of this contribution, cobalt layers epitaxially grown on hematite, has been extensively studied as a prototypical exchange coupled metal-oxide system [2]. Here, we use the ultrathin FM Co layer to control the antiferromagnetic state of hematite, similarly as previously presented for the CoO/Fe system [3].

We have performed the comprehensive studies of Co/α-Fe_2O_3(0001) heterostructures using chemical and magnetic sensitivity of synchrotron methods: X-ray photoemission electron microscopy (X-PEEM), X-ray absorption spectroscopy (XAS), X-ray magnetic circular dichroism (XMCD) and X-ray magnetic linear dichroism (XMLD). Additionally, hematite stoichiometry and orientation of the Néel vector was verified using conversion electron Mössbauer spectroscopy (CEMS).

Hematite α-Fe_2O_3(0001) films, typically 10 nm thick, were prepared in an ultrahigh vacuum system by oxidizing magnetite Fe_3O_4(111) films, grown on MgO(111) substrates with Pt(111) buffer layers using oxygen-assisted molecular beam epitaxy. Then, 1 nm of cobalt was deposited at RT. A reference area without Co was also included.

The XMLD-PEEM (at the Fe edge) and XMCD-PEEM (at the Co edge) measurements were performed at the SOLARIS synchrotron [4]. The AFM domains of hematite are shaped by the FM domain structure of cobalt. On the other hand, the Co film on hematite leads to secondary changes in the shape and contrast distribution of the AFM domains. Furthermore, by using permanent magnets that generate a moderate magnetic field of approximately 140 mT at the sample, we were able to implement remagnetisation experiment in the PEEM microscope. Surprisingly, while the bare hematite film resisted the magnetic field, the AFM domains under the Co layer followed the remagnetisation process of the cobalt film. In addition, the XMLD-XAS and XMCD-XAS measurements were performed, in which it was possible to control the direction of the external magnetic field relative to the easy magnetization axes. These measurements were helpful in interpreting the microscopic images measured in PEEM.

This research was funded by National Science Centre, Poland (NCN), grant number 2020/39/B/ST5/01838.

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Structural and magnetic properties of patterned SmCo films

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SmCo micromagnet gained large interest in the scientific community due to their high coercivity and high capability of energy storage, which make them good candidates for many device applications such as Micro-Electro-Mechanical Systems (MEMS) [1, 2]. In this work we have studied the effect of patterning on structural and magnetic properties of W/SmCo/W heterostructures by a more fundamental approach focusing of the micro-magnets characterization.

Thick SmCo films of 500 nm thickness deposited by RF sputtering in W/SmCo/W structures on Si substrate (Fig 1a). Micron-sized W/SmCo/W micromagnets (150 × 20 μm) fabricated by optical lithography and ion beam etching (Fig 1b). Phase composition, surface

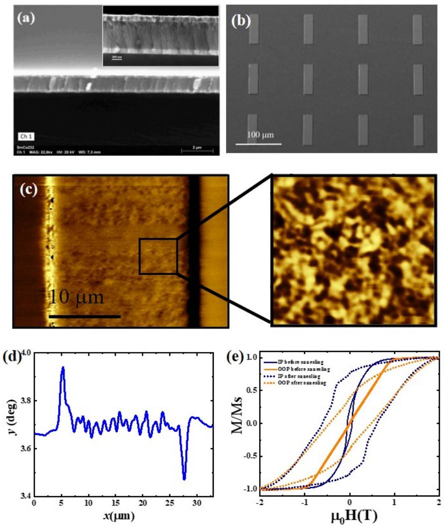

Figure 1: (a) SEM cross section of continuous SmCo film before annealing, (b) SEM image of patterned micromagnets (top view). (c) MFM images of micromagnet with zoomed area, and (d) MFM profile. (e) The in-plane (—) and out-of-plane (---) magnetic hysteresis of SmCo films before and after annealing at 650°C for 60 min.

quality, absence of impurities, Sm/Co ratio were verified by XRD, AFM, EDX and XPS techniques. The SmCo film has good stability with low roughness and without delamination during the postdeposition annealing process. The granular structure of the SmCo film found after height vacuum annealing at 650°C for 1 h. Well-formed granular structure of magnetic domains inside the micromagnets has been found (Fig. 1c). The edge effect due to strong scattering fields is well visible at the edge of the micromagnet according to the MFM data (Fig. 1d). COMSOL simulations checked out the effect of edge size of micromagnet and it is in good agreement with the MFM and VSM data (Fig. 1e).

This work was supported by the Joint Research Centre scientific partnership between Politecnico di Milano and STMicroelectronics and by the European Fundig https://mandmems.eu (EU Project 101070536 — MandMEMS). The authors acknowledge the availability of experimental facilities at PoliFAB.

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Investigating Orbital Hall Effect Materials for Efficient Magnetization Control

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There is considerable potential in leveraging the Orbital Hall Effect (OHE) and the Spin Hall Effect (SHE) as electrical approaches for controlling the magnetization of spintronic devices [1], [2], [3], [4]. Ruthenium emerges as a promising candidate, exhibiting an orbital Hall conductivity four times greater than that of Platinum [5], [6]. Recently, Ru and Nb have gained attention for their apparently significant generated orbital torque [7], [8].

This work assessed the efficiency of four distinct stacks in devices featuring 100 nm Magnetic Tunnel Junctions (MTJ) with perpendicular magnetic anisotropy. The stacks are based on Ta/OHE/Pt/$[Co/Ni]_3$/Co/MgO/CoFeB/Ta/Ru, where the OHE materials are Ru, Nb, and Cr. Additionally, a Ta/Pt/$[Co/Ni]_3$/Co/MgO/CoFeB/Ta/Ru sample serves as a reference, where the thickness of Pt matched that of Pt and OHE in the other samples.

We demonstrate an improvement in the Ru samples, exhibiting 30% higher damping-like torque and 20% lower switching current density than the Pt reference sample. These findings, along with their alignment with first-principle calculations, underscore the potential of Ru as an OHE material for enhancing the performance and reducing power consumption of spintronic devices [9].

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Orbital currents and torques on transition metals using interfacial orbital Rashba effect

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Recent works provide strong evidences of a large orbital Rashba-Edelstein effect (OREE) at the interface between Cu and its oxide [1]. Some focused especially on the observation of a torque enhancement due to a naturally oxidized Cu layer (presenting a Cu/CuOx interface) on top of a conversion Pt layer. In these systems, the enhancement is attributed to an orbital current generation by OREE at Cu/CuOx interface, converted in spin-current by the large spin-orbit coupling of Pt. For specific values of the Pt thickness and for insulating ferromagnets, a large enhancement of the net torque has been measured [2] as well as an enhancement of spin injection detected through spin-pumping measurements [3]. Here we experimentally demonstrate that a very large enhancement (up to a factor of 2) of both the net torque and the spin-pumping voltage can be obtained in full transition metals systems Co/Pt/Cu* [4] (Fig. 1), where Cu* stands for a naturally oxidized Cu layer.

In ferromagnets, the spin decoherence length is known to be very short, when for orbital currents a different coherence length might exist. To disentangle spin and orbital currents in these systems, we performed the ferromagnet thickness dependence of the net torques and

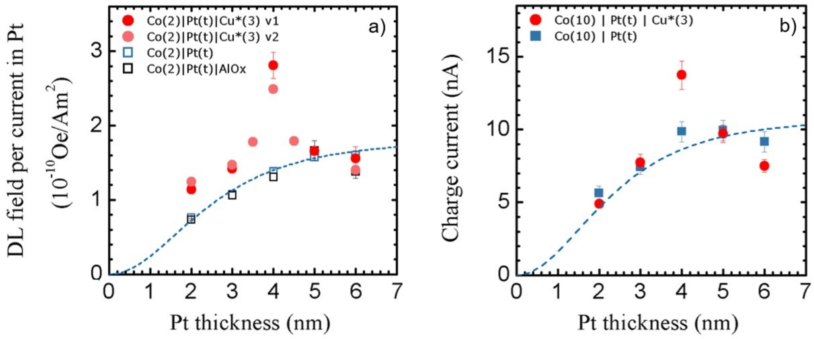

Figure 1: Pt thickness dependence of systems with and without generation of orbital currents in copper. a) damping-like field per current in Pt, b) spin and orbital pumping measurements driven by FMR.

observe a clear increase of the corresponding dephasing length, indicating the contribution of pure orbital currents acting on the magnetization. Finally, we investigate the Cu thickness dependence which indicates an interfacial generation of orbital currents, as well as the structural and chemical properties of our samples by X-ray PhotoElectron Spectroscopy (XPS) and Transmission Electron Microscopy (EELS and EDX) measurements.

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Large Interfacial Rashba Torques in Atomically Thin Co|Al Systems

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We have investigated the spin-orbit torque properties as well as the manipulation of the magnetization in Pt|(Co,CoFeB)|Al|Pt systems by adding a thin light element (Al) in contact with an ultrathin Co and/or CoFeB 3d transition metal ferromagnet (TM). The resulting torques obtained by f-2f second harmonic techniques are then shown to arise from both the spin Hall effect of Pt via the spin-orbit interactions and via the Rashba Edelstein effect, possibly from orbital origin at the Co|Al interface.

We found in our systems a strong enhancement of the field-like torques emerging from the TM Co|Al interface which may be assigned to the occurrence of an orbital momentum locking and subsequent orbital Rashba effect at the Co|Al interface [1]. We discuss then common issues and differences by using CoFeB or combined Co|CoFeB systems instead of sole Co. Those samples have a much smaller magnetic anisotropy than Pt|Co|Al.

In a second part, we will present results of current-induced magnetisation switching obtained on 250 nm size nanopillars patterned by e-beam lithography and made from the same aforementioned stacks. We will extensively discuss the gain observed and reported on the critical current densities for various Co and CoFeB systems. This will be corroborated to the corresponding magnetic anisotropy of each system.

The last part of our study consists in measuring the dependence of the critical currents on the electric pulse width. We will discuss how this can shed light on the switching mechanism and on how a strong field-like torque might contribute to current-induced magnetization switching.

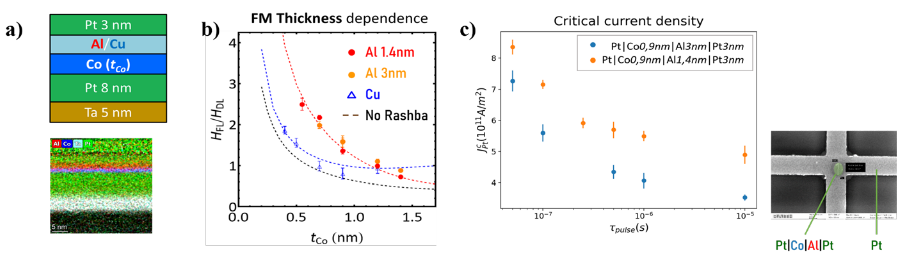

Figure 1: **a)** *Top:* Example of the stacks we have investigated. *Bottom:* Energy dispersive X-ray spectroscopy elemental map showing low intermixing between the layers. Extracted from [1] **b)** Dependence of the ratio between field-like and damping-like torques as a function of the thickness of the ferromagnetic layer [1]. **c)** Magnetization switching critical currents as a function of the current pulse width. The inset is a SEM image of the devices we fabricated.

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Nanosecond scale stochastic magnetization reversals in perpendicular superparamagnetic tunnel junctions

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Magnetic tunnel junctions (MTJ) are nanoscale magnetic devices first developed as memory storage units and have recently appeared as promising stochastic building blocks for cognitive computing. An MTJ comprises two ferromagnetic metallic layers separated by a thin oxide layer. In this multilayer system, the magnetic direction of the two layers can be either parallel or anti-parallel (P or AP), which defines then the two possible states of the junction. Due to tunneling-magnetoresistive effect those two states have two different resistance levels, this enables an electrical reading of the device's magnetic state which is used to encode binary information.

At non-zero temperature, energy arising from thermal fluctuations (kT) enables to overcome the energy barrier separating the two states, and induces random switching between AP and P. Such thermally-induced transitions define a mean dwell time ($\tau_{AP(P)}$) for each state $\tau_{AP(P)} = \tau_0 \exp(E_b(AP(P))/kT)$ where τ_0 is a prefactor, set as constant to 1 ns, within the commonly used macrospin models[1]. For low enough values of E_b, the MTJ is superparamagnetic (SMTJ) with typical dwell times that can range from milliseconds to nanoseconds. Despite the random nature of thermally induced magnetization reversal in the SMTJ, the probability of being in one of the two states can be controlled deterministically through both applied current and magnetic field. This capability to generate a tunable and fast Random Telegraph Noise (RTN), induced from thermal energy has made SMTJ highly appealing for numerous low-energy cognitive applications.

SMTJs with in-plane magnetic easy axis exhibit state-of-the-art nanosecond scale mean dwell time[1,2]. However, those in-plane structures have limited potential in terms of scalability, as their properties are highly shape dependent. MTJs with perpendicular magnetic easy axis (pMTJs) are therefore the one used in commercially available devices.

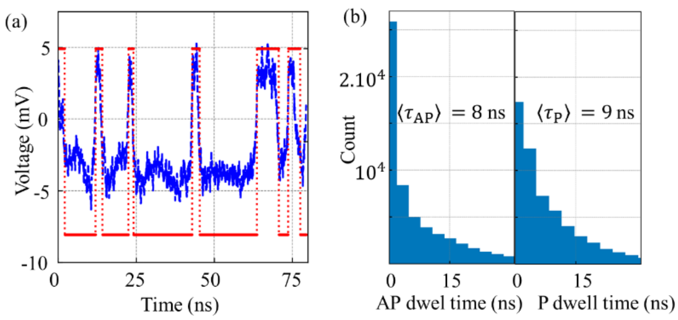

Figure 1 :(a) RTN at the nanosecond scale measured in 50 nm diameter nanopillar perpendicular SMTJ for applied voltage of 675 mV and 30 mT external field. (b) The Corresponding histogramm of the AP/P mean dwel times

In this work, we investigate RTN in 50 nm diameter SMTJs with perpendicular magnetic easy axis. By fine-tuning of E_b, we experimentally measure RTN with dwell time as short as 8 ns (Fig.1). We report a large tunability on the estimated dwell times through applied DC current and external field. Describing the mean dwell times observed in those SMTJs requires models beyond the traditional macrospin approach. Through micromagnetic simulation that reproduces well our experimental results at a small bias voltage, we show that the magnetization reversal occurs through a domain wall, which reduces the Arrhenius prefactor τ_0 down to the femtosecond scale.

This work hereby paves the way toward implementing THz-operating fast stochastic binary neurons for cognitive computing, with scalability down to tens of nanometers using perpendicular magnetic stacks.

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Electrical control of exchange bias in HfO_2/CoO/Co heterostructures through voltage-driven oxygen ion motion

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Exchange Bias (EB) is an interfacial effect that typically appears in coupled ferromagnetic(FM)-antiferromagnetic(AFM) layered systems. Field cooling the FM-AFM system from above the Néel temperature while applying an external magnetic field, high enough to saturate the FM, is needed to induce this effect. EB manifests as a horizontal shift of the hysteresis loop and it is linked to the exchange coupling of the magnetic moments at the FM-AFM interface [1]. From a technological viewpoint, EB systems like spin valves or magnetic tunnel junctions are part of MRAMs and read heads of hard disk drives. The electrical control of EB holds the potential to improve performance of these devices from an energy-efficiency viewpoint [2].

Here the EB strength in the HfO_2/CoO/Co heterostructures, grown by magnetron sputtering, is electrically controlled by tuning the amount of oxidation of Co using voltage-driven motion of oxygen ions from HfO_2 to Co. Magnetoelectric measurements were carried out at room temperature by performing vibrating sample magnetometry while actuating with voltage through liquid electrolyte-gating. Different applied voltages were used to trigger the formation of dissimilar amounts of CoO. EB characterization was carried upon field cooling from room temperature down to 25 K. Exchange bias properties were investigated as a function of temperature. No matter which voltage is applied, no EB effect is observed above 200 K, indicating that the blocking temperature of all systems falls between 100 and 200 K, evidencing size-effects in CoO due to its nanostructured nature. For all temperatures below 200 K, the EB shift scales with voltage. Interestingly, application of positive voltage induces an enhancement of EB in the whole temperature range down to 25 K. This effect can be ascribed to a decrease of the FM layer thickness with increasing voltage, which is known to enhance the EB effect [1] because of its interfacial character.

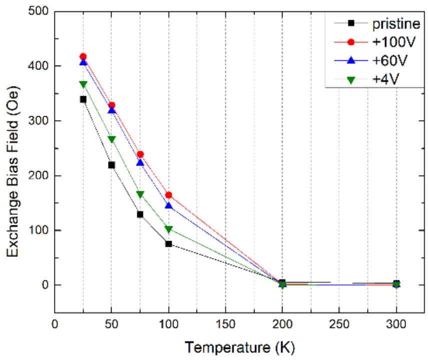

Figure 1: Evolution of the EB shift as a function of increasing temperature for the heterostructures subjected to 4, 60 and 100 V for 60 min and field cooling from room temperature down to 25 K.

[1] J. Nogues, I. K .Schuller, J. Magn. Magn. Matter., **192** (1999), 203-232.

[2] C. Navarro-Senent, et.al., APL Mater, **7** (2019), 030701

Electric field control of magnetization in FeGa microstructures on PMN-PT

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In current generation memory devices, the significant usage of electric currents to control large number of magnetic bits inevitably results in large power consumption and also power losses due to Joule heating. In this regard, a new paradigm has been formed where the possibility of manipulating the magnetization using electric fields (rather than electric currents) are currently being explored [1]. Artificial magnetoelectric (ME) materials are suitable candidates to be used in these technologies due to its coupling between magnetization and electric-field induced strain, which therefore consumes less power and significantly reduces heat losses [2].

We have investigated the magnetic properties of FeGa microstructures on PMN-PT under electric-field cycles (Figure 1(a)). Initially, the piezoelectric domains were studied to interpolate the correlation with the magnetic domains. Figure 1(b) shows the crystalline topography, disordered (pristine) and linear stripes (polarized) ferroelectric domains in PMN-PT recorded using piezo-response force microscopy (PFM). In the pristine state (as-deposited state before application of electric field), the magnetic states in disks were recorded using magneto-optic Kerr effect (MOKE) microscopy. The study of magnetic domains revealed the presence of single (green circle) and double vortex (yellow circle) states in the samples (Figure 1(c)). The magnetic domains states are currently being investigated at different strained states achieved by using specific electric field processes. The circularity and polarity of the vortex states are studied using magnetic force microscopy (MFM). Further, the switching of in-plane magnetization in FeGa thin films of similar thickness has also been performed under a cycling ON-OFF electric field, showing non-volatility and reversibility (Figure 1(d)) [3].

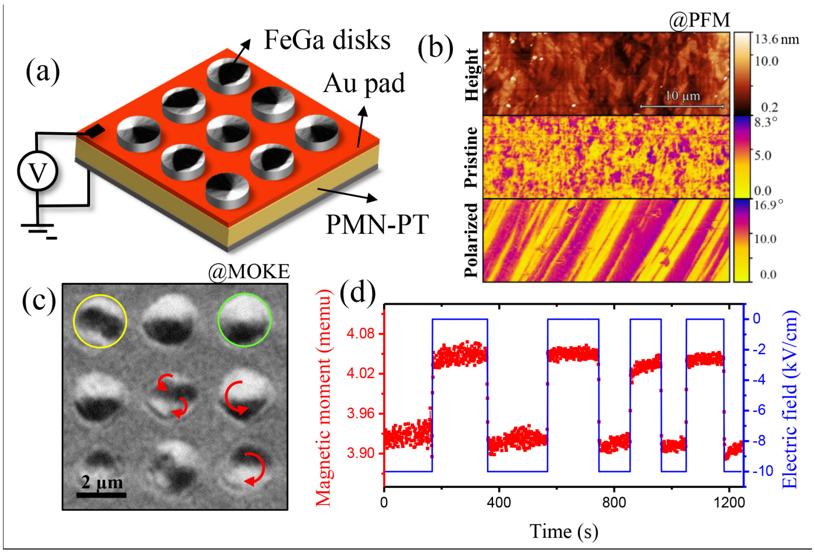

Figure 1: (a) Schematic of FeGa/PMN-PT heterostructure for electric field application. (b) Topography, pristine and polarized ferroelectric domains of PMN-PT. (c) Magnetic vortex states in FeGa disks. (d) Switching of magnetization with ON-OFF electric field.

[1] N. A. Spaldin and R. Ramesh. Nature materials 18.3 (2019): 203-212.
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[3] G. Pradhan, et al. Journal of Physics: Materials 7.1 (2024): 015016.

Magnetism of pure and Fe-doped multiferroic CoCr2O4 thin films

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Multiferroic materials allow control of magnetic states through electrical potentials and vice versa. Single-component multiferroics are rare, however, and often have low transition temperatures and weak magnetization. As thin films, their properties can be changed considerably from their bulk counterpart, due to their high sensitivity to lattice strain and stoichiometry, which open routes to control selective properties. Here we focus on the thin film multiferroic $CoCr_2O_4$ (CCO). Bulk CCO has a ferrimagnetic transition at 95 K with a net moment of 0.08 μB/f.u.

We present an investigation of thin films of pure and Fe-doped CCO grown with different crystallographic orientations and strains on MgAl2O4(001) (MAO) and Al2O3(0001) (ALO) substrates. Polarized neutron reflectometry (PNR), muon spin relaxation (μSR), and magnetometry provide a comprehensive picture of the magnetic properties (Figure 1). Combined with structural evaluation techniques (e.g. Figure 1a) we obtain a detailed picture of the film morphology. Both PNR and μSR reveal a homogeneous magnetization profile throughout the films (Figure 1c+d) with magnitudes exceeding those of the bulk, e.g. 0.18 μB/f.u. at 2 K for CCO/MAO(100), more than twice the bulk value [1]. Despite the significant strain created by an approximately 3% lattice mismatch, interfaces with the substrates remain sharp. μSR reveales details of the magnetic transitions, including a dependence of the magnetic transition temperature on the two different substrates (Figure 1d), a clear depth dependence, and strong enhancements with Fe doping (e.g. an increase from 85 K to 125 K for x = 0.075 in $Co(Cr_{1-x}Fe_x)_2O_4$) that is particularly difficult to detect with magnetometry due to sublattice compensation. The effects of different Fe-doping concentrations will also be discussed.

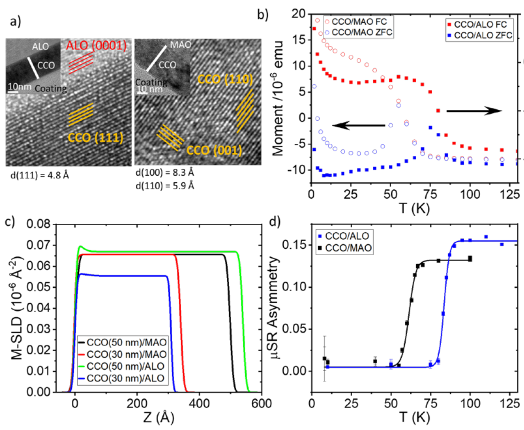

Figure 1: Examples of the structures and magnetism of different $CoCr_2O_4$ thin films. a) TEM. b) Volume averaged M vs T. c) Magnetization depth profiles obtained from PNR in 4 T. d) μSR T dependence of asymmetry.

[1] Y. Yamasaki *et al.* PRL **96**, (2006) 207204. [2] R. Padam *et al.* APL **102**, (2013) 112412. [3] J.A. Heuver *et al.* PRB **92**, (2015) 214429. [4] R. Guzman *et al.* PRB **96**, (2017) 104105.

Complex non-collinear spin structure of a Mn double layer on Ag(111)

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Non-collinear spin structures in ultrathin transition-metal films are promising for spintronic applications and can be stabilized by competing magnetic interactions. Higher-order exchange interactions have been shown to induce nontrivial spin structures such as the 3Q state in a Mn monolayer on Re(0001) [1,2] and a conical spin spiral state in a Mn double layer on W(110) [3]. The Ag(111) surface is a different type of substrate than the heavy transition-metals Re or W since it exhibits only a weak hybridization with magnetic overlayers and a small spin-orbit interaction. Therefore, exchange interactions within the Mn double layer should play a dominant role. Here, we present first-principles calculations for a Mn double layer on the Ag(111) surface using density functional theory as implemented in the FLEUR code [4]. We reveal a complex three-dimensional magnetic ground state which is created by a coupling of a row-wise antiferromagnet to a spin spiral state due to higher order interactions (Fig. 1).

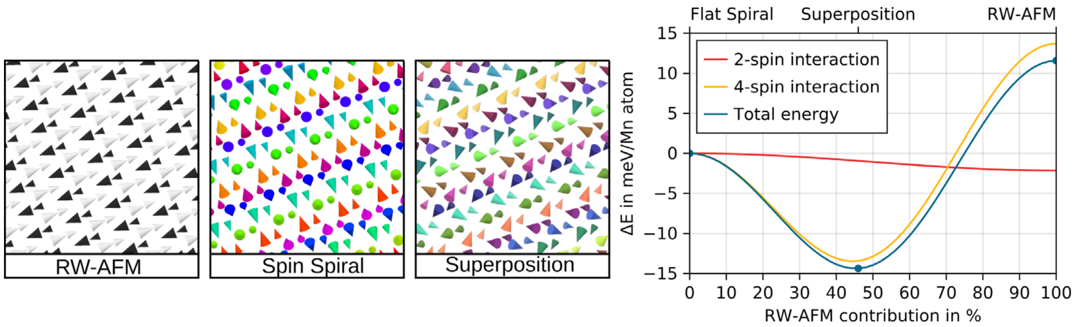

Figure 1: Left: Magnetic moments in the row-wise antiferromagnetic (RW-AFM) state, the spin spiral state and their superposition in the Mn double layer, represented by large and small cones for the top and bottom Mn layer, respectively. Right: Energy of the superposition state (blue) as function of the mixing between spin spiral and RW-AFM state. The contributions of Heisenberg exchange (red) and higher-order exchange (yellow) are shown separately.

[1] Spethmann *et al*., Phys. Rev. Lett. **124**, 227203 (2020).

[2] Haldar *et al.* Phys. Rev. B. **104**, L180404 (2021).

[3] Yoshida *et al.* Phys. Rev. Lett. **108**, 087205 (2012)

[4] The FLEUR project: www.flapw.de

Topological magnon gap engineering in van der Waals CrI_3 monolayer

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In the recent years, ferromagnetic van der Waals crystals received enormous attention due to their magnetic properties like the existence of the gap along with the topological states at Dirac points. There have been many debates about the origin of the topological magnon band gap in these materials since two main models with distinct characteristics, i.e., Dzyaloshinskii-Moriya (DM) and Kitaev, provided possible explanations with different outcome implications [1, 2]. Here we investigate the angular magnetic field dependence of the magnon gap of CrI3 using stochastic atomistic spin dynamics simulations together with linear spin wave theory to determine the main differences between Kitaev and DM models [3]. We observe three distinct magnetic field dependencies between these two gap opening mechanisms. First, we demonstrate that the Kitaev-induced magnon gap is influenced by both the direction and amplitude of the applied magnetic field, while the DM-induced gap is solely affected by the magnetic field direction. Second, the position of the Dirac cones within the Kitaev-induced magnon gap shifts in response to changes in the magnetic field direction, whereas they remain unaffected by the magnetic field direction in the DM-induced gap scenario. Third, we find a direct-indirect magnon band-gap transition in the Kitaev model by varying the applied magnetic field direction. These differences may distinguish the origin of topological magnon gaps in CrI_3 and pave the way for exploration and engineering topological gaps in other van der Waals magnetic materials.

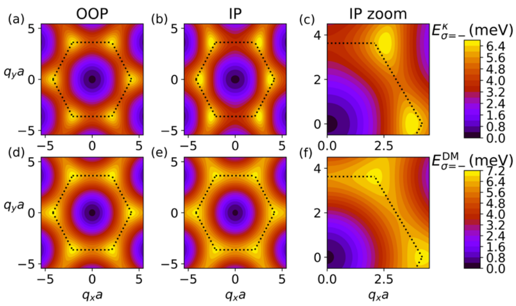

Figure 1: Positions of the Dirac-like cones in the magnon dispersion relation with constant-energy cuts at out-of-plane (OOP) and in-plane (IP) orientation of the external magnetic field (4.5 T). In the Kitaev model (a-c) and Dzyaloshinskii-Moriya (DM) model (d-f).

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Scattering of magnetostatic surface modes of ferromagnetic films by geometric defects

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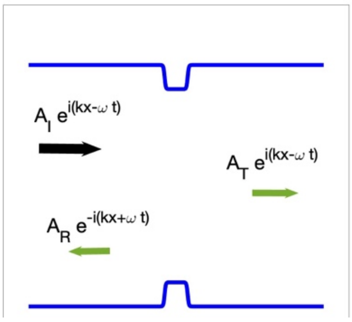
Universidad de Chile

A problem of interest in the area of Magnonics is the propagation of spin waves in thin ferromagnetic films or stripes. Presently this interest is related with the possibility of using spin waves as a practical mechanism of transferring information within nano-devices, either coded in their amplitudes or phases. In particular, to elucidate the effect of geometric obstacles or simply roughness in their propagation is of relevance for practical applications. The present study focuses on the scattering of particular spin wave modes in a particular geometry of interest: the propagation of magnetostatic Damon-Eshbach surface waves [1] in ferromagnetic films, these are modes that propagate perpendicularly to the magnetization and that may have high group velocities. We consider that the surfaces of the films have localized geometric modulations perpendicular to the direction of propagation of the waves, that may be of arbitrary shape, but in particular we consider in this study bumps and depressions. The analysis of the effect of the obstacles in the spin wave flow of energy allows to define transmission and reflection coefficients of the scattering process. These coefficients may be simply obtained in terms of phase shifts of even and odd modes that describe the scattering solutions of the same frequency.

We determine these spin wave modes with symmetry properties through the Green-Extinction theorem [2,3], that renders sets of integral equations for the modes evaluated on the geometrically modified surfaces: at the end a standard matrix eigenvalue problem renders the frequencies, shape of the modes and their phase shifts.

Depending on the shape of the obstacles, from the band of surface modes we do see emerging localized modes: these emerge from the highest frequency of the band, that corresponds to the frequency of surface modes in semi-infinite media. Also, depending on the shape of the obstacles the transmission coefficient presents frequency dependent regions of high transmission, that are associated with resonant modes of the geometry [4].



Depressions act as effective "potential wells" since in them resonances are associated with incoming waves with fractions of their wavelengths fitting the depressions approximate length.

[1] R.W. Damon and J.R. Eshbach, J. Phys. Chem. Sol. 19, 308 (1961).

[2] Arias, Rodrigo and Mills D.L., Phys. Rev. B 70, 094414 (2004).

[3] Arias R.E., Phys. Rev. B 94, 134408 (2016).

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Magnetic properties of $Fe_3Si/\alpha\text{-}FeGe_2/Fe_3Si$ multilayer films

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Layered magnets are ideal platforms for exploring magnetism in the 2D limit [1]. To establish their potential in future technologies, the realization of high-quality magnetic layered materials exhibiting ferromagnetism (FM) and/or antiferromagnetism (AFM) close to room temperature is urgently needed. Recently, we have successfully synthesized at wafer-scale a metastable α-$FeGe_2$ layered phase using a combination of MBE and solid-phase epitaxy (SPE) down to only 4 nm in vertical trilayer stacks sandwiched between ferromagnetic Fe_3Si Heusler alloys [2]. Comprehensive X-ray diffraction (XRD) and transmission electron microscopy (TEM) revealed the formation of the layered α-$FeGe_2$ allotrope (space group P4mm) which does not exist as a bulk [3]. In situ transmission electron microscopy experiments revealed the dynamics of the crystallization process, where the amorphous Ge first crystallizes to disordered $FeGe_2$ under the influence of Fe diffusion into the amorphous film and then it transforms into the ordered α-$FeGe_2$ phase [4]. Spin transport investigations have revealed a metallic behavior of α-$FeGe_2$ films [5]. Strikingly, the results also indicate a FM-AFM phase transition where the films are FM at low temperatures [5]. DFT calculations support this experimental result with a ferromagnetic ground state and an antiferromagnetic state with an only slightly different total energy [5].

In order to gain more information on the magnetization behavior, SQUID measurements on various $Fe_3Si/\alpha\text{-}FeGe_2/Fe_3Si$ multilayer films on GaAs(001) substrates, a single layer Fe_3Si on GaAs(001) as well as on the bilayer system $Fe_3Si/\alpha\text{-}FeGe_2$ were performed. The thickness of the α-$FeGe_2$ layer was varied between 4 and 8 nm. Magnetization curves were recorded at temperature between 4 and 300 K. The results demonstrate a strong influence of the α-$FeGe_2$ layer on the magnetic properties of subjacent Fe_3Si already in the bilayer case. For the high-symmetry axis [010], the magnetization reversal takes place in two steps with a plateau at zero magnetization. The magnetization curves along the [110] and [-110] directions reveal magnetization reversals without intermediate steps, however, at strongly different coercive fields compared to purely Fe_3Si films. The effects enhances with increasing the thickness of the α-$FeGe_2$ layer. The magnetization behavior can be explained in general by exchange coupling effects at the $Fe_3Si/\alpha\text{-}FeGe_2$ interface most likely due to the antiferromagnetic order of the α-$FeGe_2$. The results furthermore indicate that the Néel vector in the α-$FeGe_2$ film is oriented along [-110]. The origin of the two-step magnetization reversal along the [010]-direction remains somewhat unclear, as it could also resemble the switching behavior typically observed for two nominally identical layers with slightly different coercive fields.

Regarding the layered structure and some of the observed phenomena, it is quite conceivable that α-FeGe2 emerges as a promising new material. In particular, the perspective to switch the magnetic state from FM to AFM order by external stimuli appears to be extremely attractive for spintronic applications.

[1] S. Valenzuela *et al.*, Nat. Nanotech. 14, 1088 (2019).

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Unveiling Room-Temperature Ferromagnetism in 2D Van der Waals Material: Cr_4Te_5

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Two-dimensional (2D) Van der Waals (VdW) materials have garnered significant attention across diverse research avenues due to their wide-ranging properties. The recent identification of magnetism in 2D VdW materials [1,2] has further attracted material scientists, particularly for potential advancements in magnetic spin valves and VdW heterostructures. Achieving nanoscale precision in the downsizing of 2D transition metal dichalcogenides (TMDs) is crucial for their integration into technology, with a particular emphasis on reaching the ultrathin film limit.

In this work, we demonstrate the successful fabrication of epitaxial Cr_4Te_5 thin films on Al_2O_3 (0001) substrates with precise control of thickness through pulsed laser deposition (PLD) using 1st harmonic Nd: YAG pulsed laser source [3, 4] X-ray diffraction (XRD) and scanning tunneling microscopy (STM) reveals high crystalline quality as well as atomically flat surfaces. Our investigation reveals the thickness threshold beyond which room temperature ferromagnetic order persists. Films with thickness above 20 nm found to have very high Curie temperature i.e., 350 K. We have also explored both the electronic and magnetic properties of Cr_4Te_5, employing both experimental techniques and theoretical analyses. Our findings indicate a predominant in-plane ferromagnetic character, with spin-orbit coupling playing a significant role in promoting ferromagnetic order. Our study enables Cr_4Te_5 TMD's as a promising material for the development of room-temperature magnetic devices and sensors applications.

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[3] P. Orgiani *et al.*, *Rev. Sci. Instrum.*, vol. 94, no. 3, p. 033903, 2023.
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Magnon-Phonon coupling in Fe_3GeTe_2

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Fe_3GeTe_2 (FGT) is a ferromagnetic, two-dimensional (2D) van der Waals material that hosts collective excitations in form of magnons and phonons at the same time [1]. Here we study the dynamic coupling of magnons and acoustic phonons in single crystals of FGT using inelastic scanning tunnelling spectroscopy (ISTS) with an ultra-low temperature scanning tunnelling microscope [2]. Inelastic scattering of hot carriers off phonons or magnons has been widely studied using ISTS, and we extend the technique to study magnon-phonon coupling. We show a strong interaction between magnons and acoustic phonons leading to in avoided band crossings and hybridization between the magnonic and phononic bands, which lifts the constrains set by the selection rules for their individual excitation by electrons. We identify these additional hybridization points in experiments and compare their energy to density functional theory calculations. Our findings provide a platform for designing the properties of dynamic magnon-phonon coupling in two-dimensional materials in form of phonon-localization in magnetic domain walls or magnon localization by strain fields, and discuss the role of phonon-magnon coupling in Gilbert damping.

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Magnetotransport in 3D and 2D nonstoichiometric and Mn-doped Bi_2Te_3

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3D topological insulators (TIs), such as bismuth telluride (Bi_2Te_3), can be characterized as materials of an insulating/semiconducting volume and topologically protected conductive surface states. The surface states form a characteristic spin-momentum-locked Dirac cone due to the linear dispersion relation. Such an electronic structure makes TIs a very promising candidate both for research on their unique phenomena related to this non-trivial topology and for potential applications. However, due to structural defects in a real sample, the Fermi level (E_F) located in the gap for the volume states is difficult to be achieved [2]. Thus, a control over their electronic structure is important to satisfy the theoretical predictions and increase the scope of technological applicability.

It is possible to obtain information about the energy levels and the density of states by applying a magnetic field in different directions and measuring the change in resistance. In the presence of a magnetic field perpendicular to the sample plane, the energy states are quantized and discrete Landau energy levels appear [2]. Since only carriers with energies close to E_F can participate in transport, a rapid increase in the density of states by the Landau level causes a rapid increase in conductivity. In this way, as the E_F passes through the Landau levels, oscillations in conductivity or resistance as a function of the magnetic field, known as Shubnikov–de Haas (SdH) quantum oscillations, may be observed.

In this contribution, we compare the electronic structure of $Bi_{2-x}Te_{3+x}$ probed by SdH oscillations, for x up to 0.14, with that detected locally by scanning tunnelling spectroscopy and calculated by DFT (with respect to the carrier concentration and the model including all structural defects identified qualitatively and quantitatively by scanning tunnelling microscopy).

Moreover, we report on exfoliated flakes (quasi-2D samples) of $Bi_{2-x}Te_{3+x}$ featuring topologically protected conductive one-dimensional boundaries, which allow electrons to travel only in two directions (as a consequence of spin-momentum locking, all the electrons traveling in one direction are of the same spin orientation). Doping Bi_2Te_3 with magnetic ions breaks the time reversal symmetry, allowing one travel direction to exist without the other one, i.e. the so-called quantum anomalous Hall effect (QAHE) [3].

In particular, we discuss the results of magnetoresistance and Hall effect measurements at sub-Kelvin temperatures for an Mn-doped Bi_2Te_3 TI for both as-grown single crystals and 2D flakes. The results for a ~30 nm thick flake have shown that exfoliation does not affect the magnetic properties of the flake and a fractional QAHE has been observed. Still, SdH oscillations have not been detected yet.

Project supported by the program “Excellence initiative research university” for the AGH University of Krakow.

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Spin- and orbital-charge conversion at the surface states of Bi1-xSbx Topological insulators

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Topological insulators are quantum materials characterized by Time-reversal protected surface states (TSS) which make them appealing candidates for the design of next generation of highly efficient spintronic devices. The very recent demonstration of large transient spin-charge conversion (SCC) and subsequent powerful THz emission from Co|$Bi_{1-x}Sb_x$ bilayers clearly demonstrate such potentiality and feasibility for the near future [1-3]. Amongst the exotic properties appearing in and at the surface of such quantum materials, spin-momentum locking (SML) remains as a key ingredient to effectively convert the spin degree of freedom into a charge or a voltage signal. In that sense, in this work we will provide some clear theoretical and numerical insights implemented by multiorbital and multi-layered tight-binding methods (TB). These developments clarify our recent experimental results obtained by THz-TDS spectroscopy techniques in the time domain [2]; and allows us to disentangle the various magnetic SCC contributions. Taking advantage of their spin-momentum locking property, we also postulate the occurrence of Orbital-to-charge conversion (OCC) taking place also in these aforementioned experiments at equal footing to SCC.

By extending the spin-to-charge conversion theory, we postulate the emergence of its orbital counterpart, namely the Orbital-charge conversion (OCC), covering different contributions in terms of the orbital degree of freedom. Our results unveil the interest and prospects for the use of specific materials as source of both spin and orbital current (as Ni); and we may anticipate the advantage of using lighter elements with the restricting requirement of large SOC would be avoided in the latter case.

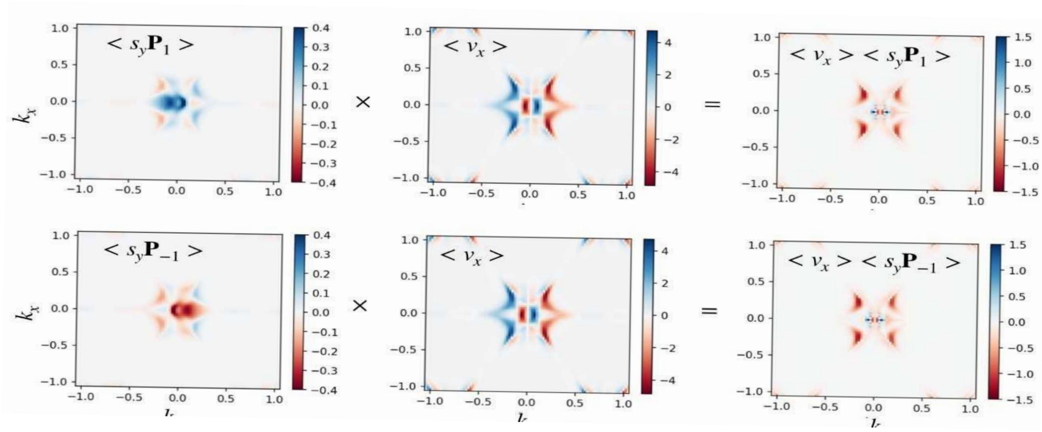

Fig. 1. Velocity and Fermi surface projection of the Orbital operator showing the distribution over the Brillouin zone.

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Floquet magnons in a periodically driven magnetic vortex

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Magnetic vortices (Fig. 1a) are prominent examples for topology in magnetism with a rich set of dynamic properties. They exhibit an intricate magnon spectrum and show an eigen-resonance of the vortex texture itself, the gyration of the vortex core. While there have been studies about magnon-assisted reversal of the vortex core polarity [1], the impact of the vortex core gyration on the magnon spectrum has not been addressed so far. The fundamental modes of both excitation types are clearly separated in their resonance frequencies. While the vortex typically gyrates at a few hundred MHz (Fig. 1b), the magnon modes typically have frequencies in the lower GHz range (Figs. 1c and d). This separation allows for experiments studying the temporal evolution of the magnon spectrum when the gyration of the vortex core is driven by an external drive. Under the influence of such a periodic driving, Floquet states emerge due to the temporal periodicity imposed on the system's ground state.

This talk delivers experimental results and numerical simulations on how the regular magnon modes in a magnetic vortex (Fig. 1d) transform into novel Floquet bands (Fig. 1e), when the vortex ground state is modulated in time by driving the vortex core gyration simultaneously. The observed magnon Floquet states are both distinct from the well-known regular magnon modes as well as from the vortex gyration and represent truly unique excitations, providing new opportunities to study and control nonlinear magnon dynamics.

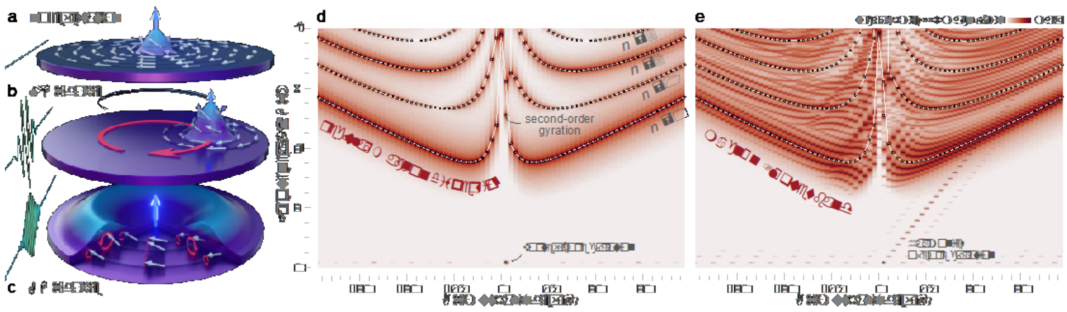

Figure 1: Schematic illustrations of (a) a static magnetic vortex, (b) a gyrating magnetic vortex driven by a MHz microwave signal, and (c) a magnon mode with lowest radial and azimuthal mode index ($n = 0$, $m = 0$). Dimensions are not to scale. (d) Simulated dispersion of thermally populated magnon modes in the vortex with a static core plotted as a function of azimuthal mode index m for different radial indices n. (f) Micromagnetic simulations of the thermal magnon population in a gyrating vortex show the magnon Floquet bands.

This work has received funding from the EU Research and Innovation Programme Horizon Europe under grant agreement no. 101070290 (NIMFEIA).

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Spin wave dispersions in ferromagnetic films with a sinusoidal magnetization distribution

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In 3D Magnonics [1], the vertical interaction between different layers can induce a non-uniform magnetic distribution in the associated ferromagnetic film layer, and in turn modify the propagation properties of spin-waves (SW). By means of micromagnetic simulations, carried out by Mumax3 software [2], we studied the case of a sinusoidal magnetization distribution in a thin film found after the relaxation of a uniform state (at 0.1 T) to an applied weaker sinusoidal magnetic field of variable amplitude (Fig. 1-a): hence, the sinusoidal field implements a possible vertical interaction induced by an overlayer of appropriate geometry, producing the magnetization of Fig. 1-b. By Fourier analysis [3], the SW dispersion relations were obtained, together with the mode spatial profiles. We also studied the relaxation to a chiral bias field (Fig. 1-c): here, the final relaxed magnetization (Fig. 1-d) shows a marked asymmetry between the two halves of the primitive cell, where magnetization and chiral field point to different directions, which is at the origin of interesting effects. The asymmetry reflects also in the SW spatial profile. In all the cases, we calculate the SW dispersions and discuss the possible occurrence of magnonic frequency gaps as a function of the sine or chiral field magnitude and its physical reasons. We also discuss the origin and behavior of the occurring flat dispersions in relation to the corresponding mode profiles and the internal effective field. The manipulation both of periodicity and amplitude of the non-uniform, undulated film magnetization impacts on the SW propagation, and can be very useful in Magnonics, either for information delivery and interferometric devices, insofar as SW modes can be tuned from propagating to stationary and vice-versa, or for signal filtering, varying the frequency gap and the number of localized modes, and possibly sensing applications as tiny variations of any dynamic properties can lead back to the tiny modifications of the magnetization due to external agents (either magnetic fields, nanoparticles, or anisotropies). PM and FM acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support.

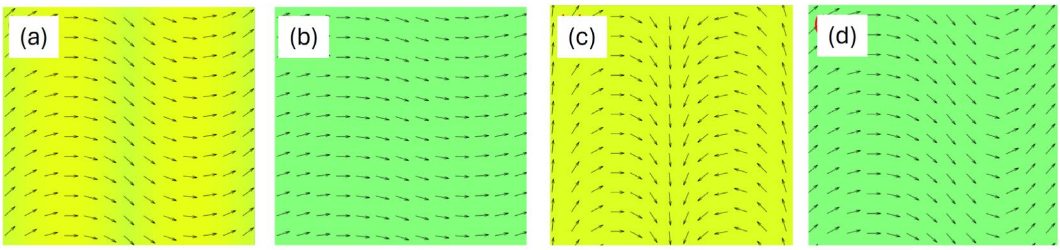

Figure 1: Illustration of the sinusoidal (a) and chiral (c) magnetic fields and the ensuing equilibrium magnetic distribution (b) and (d), correspondingly.

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Angular momentum transfer in interaction of Laguerre-Gaussian beams with ferromagnetic magnons

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The interaction between light and matter is governed by symmetries, whereby conservation laws emerge. Magnon-induced Brillouin light scattering in a continuous rotational symmetric system should conserve total angular momentum. Previously, we demonstrated the conservation of spin angular momentum between the Gaussian beams and ferromagnetic magnons in such a circumstance [1]. However, the total angular momentum conservation, including orbital angular momentum (OAM), has yet to be demonstrated. In this work, aiming at the demonstration, we identify the OAM per photon of Laguerre-Gaussian beams, L_{O}, scattered by ferromagnetic magnons with OAM per magnon, L_{M}, being either 0 or 1.

The experimental setup is schematically shown in Fig. 1(a). A spherical crystal (0.5 mm in diameter) of yttrium iron garnet (YIG) is placed at the center of the gap of a magnetic circuit and saturated by applying a magnetic field of around 150 kA/m along the crystal axis ⟨100⟩. A laser light with a wavelength of 1550 nm passes through the YIG sphere. A coupling loop coil above the YIG sphere generates an oscillating magnetic field perpendicular to the saturation magnetization to explore the Brillouin light scattering while the magnon modes are continuously driven at the resonances. Figure 1(b) shows, as an example, the observed power of Laguerre-Gaussian beams scattered by magnons without OAM, $L_{\mathrm{M}} = 0$. When the input light is a Gaussian beam with $L_{\mathrm{O}} = 0$, and the input and scattered light have the same helicity (i.e., no optical spin angular momentum change), the Stokes scattering (red bars) with optical OAM, $L_{\mathrm{O}} = +1$, appears as a principal process. In contrast, the anti-Stokes scattering (blue bars) with optical OAM, $L_{\mathrm{O}} = -1$, appears. In observed processes, the angular momentum is exchanged between the spin degree of freedom of magnon, S_{M}, and the orbital degree of freedom of light, L_{O}, where total angular momentum conservation is still valid: $\Delta S_{\mathrm{M}} + \Delta L_{\mathrm{O}} = 0$. The fact will provide new insight into the interaction between light and magnons, regardless of bulk or film magnetic materials.

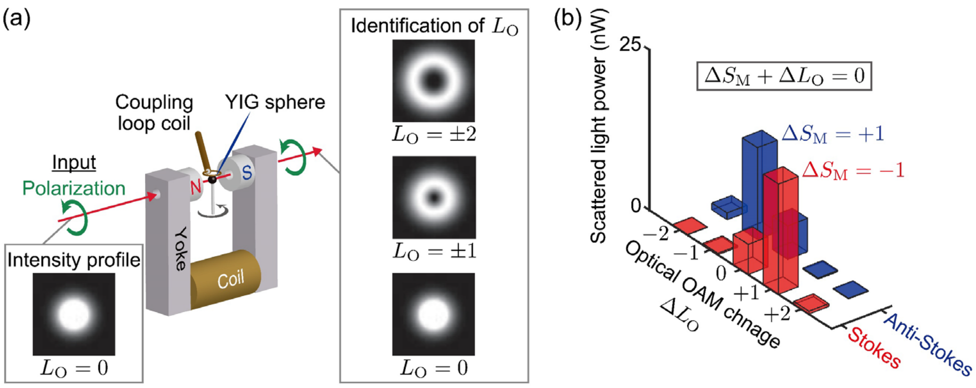

Figure 1: (a) Experimental setup. (b) Scattered light power of the Stokes sideband (red bars) and the anti-Stokes sideband (blue bars).

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Electrical control and detection of chiral spin rotation in Mn_3Sn

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Spintronics based on ferromegnets has led to the development of microwave spin-toque oscillators and diodes [1]. In these devices, magnetization precession is driven by spin current, with frequencies reaching several tens of GHz. As the frequency increases, precession cone angles typically become narrower, resulting in weakened signals. In this context, antiferromagnets hold promise. For example, in easy-plane antiferromagnets, when magnetic moments deviate from the easy plane due to spin injection, strong internal exchange fields arise and make the magnetic moments precess at current-tunable frequencies from GHz to THz without significant loss of precession amplitude. Recently, spin-torque-induced switching and rotation of a non-colinear antiferromagnetic spin structure was reported in antiferromagnetic Mn_3Sn thin films [2-4]. In the present study, we explore the electric control and detection of the antiferromagnetic resonance of the non-collinear spin structure, where coupling between microwave current and chiral spin rotation in a Mn_3Sn/W bilayer produces DC transverse voltage through rectification.

We fabricated Mn_3Sn (7 nm)/W (6 nm) epitaxial bilayers on MgO(110) substrates using molecular beam epitaxy [4,5]. The fabricated thin films were patterned into Hall bar devices by photolithography and Ar ion etching. A DC bias current and microwave current with amplitude modulation were applied through a bias-tee, and resultant DC Hall voltages were measured with a lock-in amplifier. We observed that the emergence of DC Hall voltages upon concurrent application of microwave and DC bias currents. Through numerical simulations, we revealed that the rectified signals stem from the rapid on-off switching of chiral spin rotation induced by microwave spin-orbit torque, which is similar to the spin-torque diode effect in ferromagnet.

This work was supported by JSPS KAKENHI, JST CREST (JPMJCR18T3), JST Mirai Program, MEXT-Xnics (No. JPJ011438), JST-PRESTO and Spin-RNJ.

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Epitaxial growth and Observation of Time Reversal Symmetry Breaking in Altermagnetic RuO_2

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Altermagnets, a promising new class of magnetic materials, have attracted considerable attention for their potential to revolutionize the development of innovative information technologies. These materials exhibit alternating spin polarization in both real and reciprocal space, giving them with a unique combination of collinear antiferromagnetic and ferromagnetic properties [1]. Despite having a net magnetic moment of zero, altermagnets can generate both longitudinal and transverse spin currents and a spin-splitter torque with a component perpendicular to the interface [2].

This study focuses on the epitaxial growth of RuO_2, a prototypical material for altermagnets, using pulsed laser deposition. We characterize the epitaxial growth modes using reflection high-energy electron diffraction (RHEED), investigating both layer-by-layer and island growth modes. X-ray diffraction (XRD) analysis confirms the superior quality of films grown in the layer-by-layer mode compared to the island-growth mode.

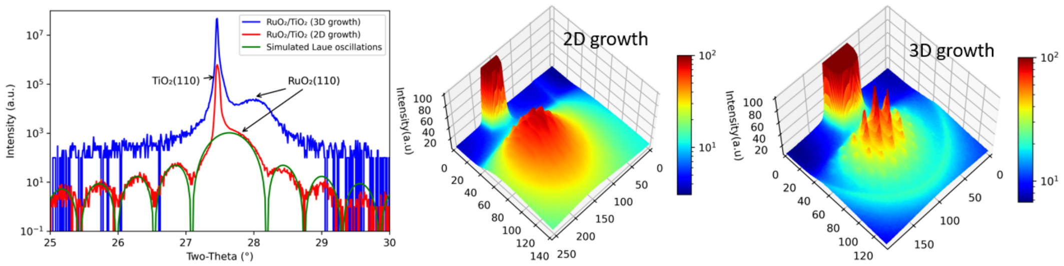

Figure 1: Left: XRD for the layer by layer growth(2D) and island growth(3D). Middle and Right: RHEED diffraction pattern for 2D and 3D growth.

We observe time-reversal symmetry breaking in the band structure of altermagnetic RuO_2 by detecting magnetic circular dichroism in angle-resolved photoemission spectra [3]. Our experimental results, supported by ab initio calculations, provide the foundational electronic structure for various phenomena and applications. These applications span fields like topological matter and spintronics which are based on the unique time-reversal symmetry breaking found in altermagnets.

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Magnetic anisotropy and magnon spin transport in antiferromagnetic α-Fe_2O_3 thin films

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We investigate the diffusive spin transport of magnons in the electrically insulating antiferromagnetic oxide α-Fe_2O_3 (hematite) [1-4]. Magnons are the quantized excitations of the spin system in magnetically ordered materials and offer a unique platform for future information technology. Antiferromagnetic materials host pairs of spin-up and spin-down magnons. We describe them in terms of a magnonic pseudospin [4,5]. Its close analogy to the electronic spin led to the prediction of novel fascinating spin transport phenomena [2-6].

The prototypical antiferromagnet α-Fe_2O_3 harbors a finite Dzyaloshinskii-Moriya interaction together with an easy-plane anisotropy. This results in a slight canting of the sublattice magnetizations in the (0001) plane at room temperature and hence in a residual net magnetic moment [7,8]. The magnonic pseudospin precesses coherently about the equilibrium pseudofield exhibiting a magnon Hanle effect, which we observe via electrical injection and detection in a two-terminal device [1-4]. We control the precession frequency via the external magnetic field. We find a non-reciprocity in the magnon Hanle signal, depending on the magnon propagation direction between spin injector and detector electrodes [2].

Upon cooling, bulk α-Fe_2O_3 exhibits a spin reorientation transition at $T_M = 263$ K from easy plane to easy axis (Morin transition), a feature often absent in thin films. To tune T_M, we investigate the impact of different growth conditions on the magnetic anisotropy [1]. Unlike for films deposited in a molecular oxygen atmosphere, we observe a finite T_M for those grown in atomic oxygen even down to a thickness of 19 nm [1]. Furthermore, we find a clear impact of the growth conditions on the magnon Hanle effect: the maximum signal is significantly enhanced and the peak position shifted to lower magnetic field values for films grown in atomic oxygen, suggesting changes in the magnetic anisotropy [1]. This shows that the growth conditions allow to fine-tune the magnetic anisotropy in α-Fe_2O_3 and thereby to engineer the magnon Hanle effect.

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Spin-charge conversion in $La_{1-x}Sr_xMnO_3/SrIrO_3$ heterostructures

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The electrical manipulation of the magnetic moment of a ferromagnetic material is of vital importance for spintronic devices, aiming to store, transmit and process information while improving energy efficiency. One of the most promising techniques is the spin orbit torque that uses spin-orbit coupling to generate a pure spin current. The efficiency of spin-charge conversion is measured through the spin Hall angle. A popular method to investigate spin Hall angle is based in the voltage measurement of the Inverse Spin Hall effect (ISHE) generated through ferromagnetic resonance (FMR). In this technique, spin angular momentum transfers from the resonating ferromagnetic material (spin generator) towards a high spin-orbit metallic material (spin sink) where it is converted to a measurable voltage by means of spin-orbit coupling. While several oxides may be used as spin generator materials (for example, YIG or manganites), the search for efficient spin sink oxides is still at its origins. One of the most promising materials are the 5d oxides due to their stronger spin-orbit coupling in comparison with their 3d analogous, and, among them, $SrIrO_3$ (SIO) have emerged as suitable candidates. Thus, to evaluate the feasibility of all oxide devices is of critical importance not only to determine the intrinsic Hall angle of the iridates oxides but also to get knowledge on different parameters that may influence an efficient spin to charge conversion as, for example, Gilbert damping, interface quality or strain release mechanisms. In this work we present our results on the study of Inverse Spin Hall Effect (ISHE) in $SrIrO_3/La_{1-x}Sr_xMnO_3$ heterostructures. Multilayers have been grown by sputtering on SrTiO3 substrates with different crystallographic orientations. Microstructure of the samples have been fully characterized by advanced X-ray diffraction. The influence of interface quality, strain relaxation and crystallographic orientation will be presented.

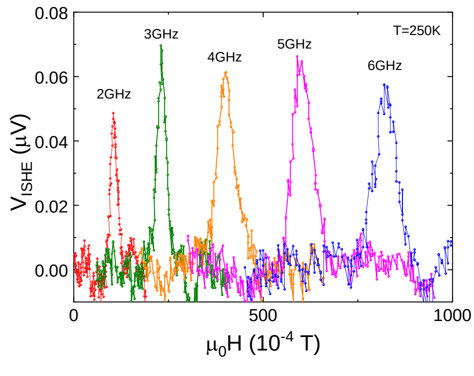

Figure 1. Inverse Spin Hall Effect voltage measured in LSMO/SIO heterostructure.

Acknowledgements The authors acknowledge financial support from the Spanish Ministry of Science and Innovation through Severo Ochoa (CEX2019-000917-S) and OXISOT (PID2021-128410OB-I00) and Serbian Ministry of Education, Science and Technological Development. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101007417 having benefited from the access provided by ICMAB within the framework of the NFFA-Europe Pilot Transnational Access Activity, proposal ID352.

Temperature gradient-driven motion of magnetic domains in a chiral magnetic metal multilayer

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Spin textures, such as domain walls [1] (DWs) and skyrmions [2], have been shown to move in response to both spin currents and entropic forces arising from temperature gradients. The spin currents arise from the flow of electrons or magnons induced by the spin Seebeck effect [3]. This current of angular momentum exerts spin transfer torques on spin textures that causes them to move towards the hot end of the gradient [4]. On the other hand, entropic forces arise since the temperature gradient leads to gradients in the micromagnetic parameters that determine the energy of the spin texture [5], which can either enhance or oppose this effect [6].

There are conflicting experimental results for skyrmions. In metallic multilayers, capable of supporting the room-temperature skyrmions needed for applications, conventional cold to hot motion was observed in in Pt/CoFeB/Ta [2], but motion from hot to cold has been observed in Pt/CoFeB/MgO [7]. Experiments on DWs are few. In Ref [1] a domain wall in the magnetic insulator YIG was reported to move towards the hot end of the system.

Here we report experiments on the motion of domains in Pt/CoB/Ir metallic multilayers in a temperature gradient. The multilayers support both PMA and a chiral DMI [8] and were patterned into 10 μm wide tracks. The domain locations were determined using magnetic force microscopy (see Fig. 1) before and after a two minute heat pulse was that applied at the point in the track (red area in schematic) where an electrically isolated Pt heater wire (purple area in schematic, SiO_2 insulator in green) crosses it. The heat pulse was generated by flowing a dc current through the heater, which generates a temperature gradient along the track. We estimate that the temperature in the region shown in Fig. 1 varies from about 340 K to 300 K across the area that was imaged during heating. After accounting for Oersted field effects by measuring average domain displacements for both directions of heater current and both senses of applied field, we find that the domains always move towards the heater. We find velocities ~1 nm/s in a temperature gradient of ~20 K/μm.

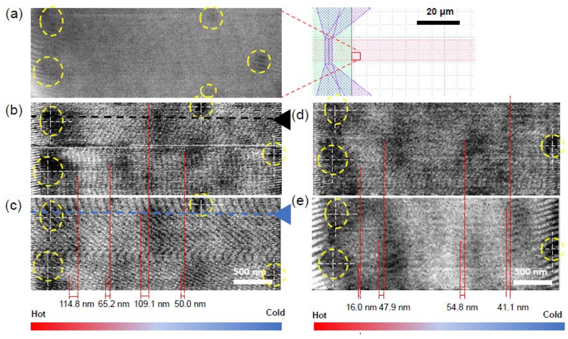

Figure 1: MFM imaging of thermal domain motion. (a) Full saturation at +700 Oe. Dark regions in the dashed yellow circles are defects used as reference markers. The schematic shows the imaged region of the track. Example MFM images in +30 Oe field: (b) and (c) before and after the heater temperature was raised to 440 K by a + 30 mA current, respectively. (d) and (e) before and after a -30 mA current. Dashed red lines show domain motion.

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Magnetic memory driven by topological insulators

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Key Words: Spin-orbit torque, topological insulators, magnetic tunnel junctions

Reducing the energy consumption is one of the major challenges for next-generation spintronic devices. Spin-momentum locking in topological surface states gives rise to a giant spin-orbit torque (SOT) efficiency, and thus to reduce the writing energy of SOT devices [1]. Here, for the first time, by combing the topological insulators (TIs) with in-plane magnetic tunnel junctions (MTJs), we demonstrate the proof-of-concept SOT-MRAM cell, where a large TMR ratio of 102% and the ultralow switching current density of 1.2×10^5 A cm^{-2} have been simultaneously achieved at room temperature [2]. The charge-spin conversion efficiency θ_{SH} is characterized by the switching field shift and the spin-torque ferromagnetic resonance (ST-FMR) methods, and the >1 θ_{SH} proves the high efficiency of topological surface states. Moreover, the all-sputtered TI-MTJ device is demonstrated, showing the potential for wafer-scale industrial applications. Next, by combing the TIs with perpendicular MTJs, we realize the all-electrical low-power writing operation by combing the SOT with a small spin-transfer torque current, with the improving thermal stability and storage density [3]. Our work proposes and demonstrates the magnetic memory driven by topological insulators, which may inspire the revolution of spintronic devices from classical to quantum materials.

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THz amplitude control in exchange-coupled Ta/Fe/RuNi spintronic emitter

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Optical laser pulses impinging at ferromagnet/metal thin film stacks can generate picosecond electro-magnetic transients with a frequency content extending into the THz range [1-3]. We fabricated $Si/SiO_2//Ta/Fe/Ru/Ni/Al_2O_3$ THz emitters in which we varied the magnetization alignment of Fe and Ni layers by interlayer exchange coupling (IEC) using different Ru layer thicknesses (t_{Ru}). Depending on IEC, magnetizations of Fe and Ni show either parallel, anti-parallel or a canted relative alignment at t_{Ru} = 1.1 nm, t_{Ru} = 1.3 nm, and t_{Ru} = 1.7 nm, respectively. As a result, THz emission shows a dramatic variation of amplitude with sub-nanometer changes of t_{Ru} in weak external magnetic fields due to an interference of THz transiens generated at the individual Fe/Ru and Ru/Ni emitters. We explore the effect of the ambient temperature and Ru thickness variations on the THz amplitude.

The work at the Research Centre Jülich (FZJ) was performed within the JuSPARC strategy project funded by the BMBF. The research at the University of Rochester was supported in part by the DOE Grant DE-SC0022473.

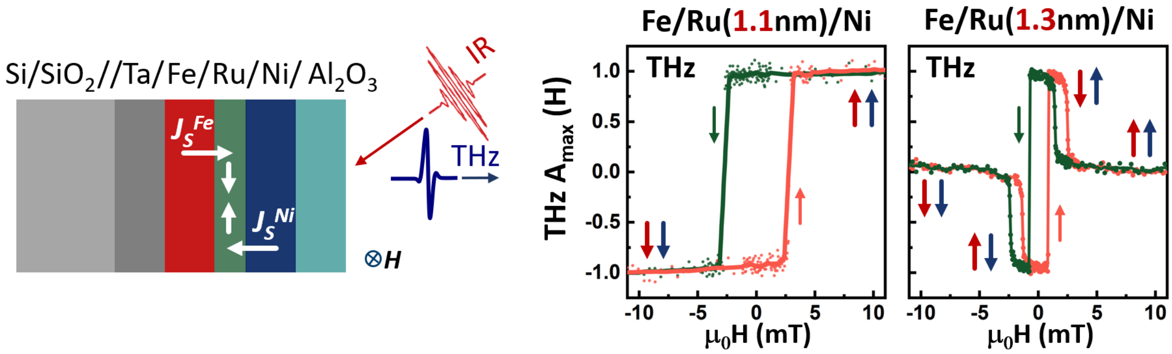

Figure left: multilayer and measurement schematics of $Si/SiO_2//Ta/Fe/Ru/Ni/Al_2O_3$ THz emitter. The horizontal and vertical arrows show the directions of the spin- and charge currents, respectively. Figures middle and right: magnetic field dependence of the maximum THz amplitude A_{max} generated by the THz emitter for t_{Ru} = 1.1 nm and t_{Ru} = 1.3 nm, corresponding to the parallel and antiparallel magnetization alignment (at μ_0H = 0 mT). The orange (green) lines and symbols correspond to the magnetic sweep from left to right (right to left). The red and blue arrows indicate the relative alignment of magnetizations of Fe and Ni layers.

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All-optical spin injection in silicon revealed by element-specific time-resolved Kerr effect

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The integration of the magnetic degree of freedom in current silicon technology is a captivating field of research which has raised renewed interest in the past few years, partly due to the increased ability to efficiently tailor the properties of hybrid metal-semiconductor devices. This path can pave the way to the SPIN Transport electRONICS paradigm, expected to improve the current Semiconductor paradigm through faster and energy-efficient devices. These achievements are made possible thanks to the unique properties of magnetism in solid systems, as for instance the spin coherence time, seemingly longer than charge confinement times, and the spin interaction energy, smaller than pure electronic interactions.

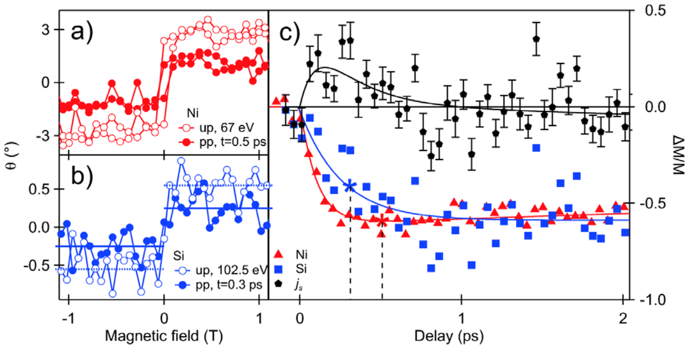

Figure 1: Unpumped and pumped RMOKE magnetic hysteresis at the Ni $M_{2;3}$ edge and at the Si $L_{2;3}$ edge (panel a and b). Panel c) dynamics of the relative change of the site resolved magnetization M (Ni - red dots and Si - blue dots) in a saturation magnetic field. From the exponential decay-recovery fit (solid lines) we extract the values for the demagnetization (τ_m) and recovery (τ_r) times. The difference of the two dynamics, defined as $(\Delta M/M)_{js}$, is also shown (gray).

A viable Spintronic technology, however, requires the effective generation, transport, manipulation and detection of spins in solid-states devices. To generate spin currents in semiconductors, the injection of spin-polarized hot electrons from a ferromagnetic film into the semiconductor substrate has been proposed. This involves the superdiffusion of the charges excited by an ultrafast IR pulse and results in an efficient spin injection. These charges during the propagation in the metallic film become spin-polarized as spin-majority scattering times and velocities are bigger than the spin-minority counterparts. Using the time-resolved resonant MOKE effect [1] we provided experimental evidence of the spin injection in silicon in the $Ni/Si_3N_4/Si$ interface both at the Ni $M_{2;3}$ and at the Si $L_{2;3}$ edges. The results proved the existence of a static magnetic state at both the edges [2], as well as the onset and the propagation of a spin current in silicon [3]. The measurements were carried out at the MagneDyn beamline [4] at the externally seeded FERMI free-electron laser.

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The MagneDyn beamline at the FERMI free electron laser

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The scope of this communication is to outline the main marks and performances of the MagneDyn beamline [1] at the Free Electron Laser FERMI which was designed and built to perform ultrafast magnetodynamic studies in solids. Open to users since 2019, MagneDyn operates with variable circular and linear polarized femtosecond pulses delivered by the externally laser-seeded FERMI free-electron laser (FEL). The very high degree of polarization, the high pulse-to-pulse stability, and the photon energy tunability in the 50-300 eV range allow to perform advanced time-resolved magnetic dichroic experiments at the K-edge of light elements, e.g. carbon and at the M- and N-edge of the 3d-transition-metals and rare earth elements, respectively. To this end two experimental end-stations are available. The first is equipped with an in-situ dedicated electromagnet, a cryostat, and an extreme ultraviolet (EUV) Wollaston-like polarimeter[2,3]. The second, designed for carry-in users instruments, hosts also a spectrometer for pump-probe resonant X-ray emission and inelastic spectroscopy experiments with a sub-eV energy resolution. A Kirkpatrick–Baez active optics system provides a minimum focus of ~20x20 μm^2 FWHM at the sample. A pump laser setup, synchronized with the FEL-laser seeding system, delivers sub-picosecond pulses with photon energies ranging from the mid-IR to near-UV for optical pump-FEL probe experiments with a minimal pump-probe jitter of few femtoseconds. The overall combination of these features renders MagneDyn a unique state-of-the-art tool for studying ultrafast magnetic phenomena in solids.

[1] Malvestuto, M. *et al.* The MagneDyn beamline at the FERMI free electron laser. *Rev Sci Instrum* **93**, 115109 (2022).
[2] Caretta, A. *et al.* A novel free-electron laser single-pulse Wollaston polarimeter for magneto-dynamical studies. *Struct Dynam-us* **8**, 034304 (2021).
[3] Laterza, S. *et al.* All-optical spin injection in silicon investigated by element-specific time-resolved Kerr effect. *Optica* **9**, 1333 (2022).

Ultrafast manipulation of antiferromagnetic order and domain wall dynamics by novel laser torques in Mn_2Au

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Finding ways to reliably control antiferromagnetic (AFM) dynamics is of great interest for high frequency spintronics. Most commonly this occurs by spin-orbit torques (SOTs) generated by either the action of current or THz radiation sources. Recently, classes of AFMs with special spin-group symmetries (such as Mn_2Au) have been shown to respond to current [1] or THz [2] excitation via intrinsic SOT [3], generating large interest in these materials. Despite of several theoretical predictions, reliable non-thermal ultrafast switching in Mn_2Au has not been proved unambiguously. Thus, finding novel roots to control AFM order is of paramount.

Here we predict another possibility for direct Nèel vector switching and DW motion in Mn2Au by the induction of staggered fields using laser-induced torques [7]. By means of atomistic spin dynamics simulations, we predict energy-efficient AFM domain switching with LOTs in Mn2Au for two special laser polarization directions. The driving mechanism relies on AFM exchange interactions, characteristic of AFM dynamics, allowing for picosecond 90 and 180-degree precessional toggle switching of the Néel vector. The toggle switching is a result of a special angular dependence of LOT as opposed to SOTs which would produce counter clock-wise circular switching with each laser pulse. Moreover, this special dependence largely prevents the over-shooting for LOT switching, characteristic to the SOT switching. Importantly, the switching is predicted to be very energy efficient. We also demonstrate the opportunity for LOTs to produce deterministic, non-toggle switching by using a combination of laser pulses with different polarizations and/or intensities.

Applying laser pulses with electric field polarization different to that of required for switching, we demonstrate that LOT can efficiently drive 90◦ DWs without changing their shape but its spatial symmetry forbids the motion of 180◦ walls. The direction of motion depends on the DW chirality. LOT-driven 90◦ DWs exhibit relativistic effects, e.g the DW width decreases as the laser intensity increases. We also show the t proliferation of DWs driven by LOT when approaching the magnonic limit.

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Controllable THz antiferromagnetic resonance frequency in NiO by cation doping: First-principles study

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Recent interest in antiferromagnetic materials has been rapidly growing in the field of spintronics, as these materials have a potential to advance spintronics technologies. For instance, intrinsic magnetism of antiferromagnets, including no net magnetization and ultra-fast spin dynamics, offers advantages in the implementation of ultrahigh-density and ultrahigh-speed magnetic memories. One of the most interesting features—and important from an application point of view—is that their antiferromagnetic resonances occur in the THz frequency range. Phenomenologically, the antiferromagnetic resonance frequency ω_r is given as $\omega_r = \gamma\sqrt{2H_{\mathrm{E}}H_{\mathrm{A}}}$, where γ is the gyromagnetic ratio, H_{E} is an exchange field, and H_{A} is a magnetic anisotropy field. In antiferromagnets, typically the H_{E} is ~1000 T and H_{A} is ~1 T, leading to the ω_r in THz order. Very recently, ω_r of NiO is experimentally explored and its modulation in a wide range covering 0.7 – 1.1 THz frequency by doping cations (Li^{+}, Mg^{2+}, and Mn^{2+}) has been demonstrated [1]. To apply such antiferromagnets to practical applications, it is of importance to establish guiding principles in tuning ω_r by doping effects.

Here, the ω_r of NiO and its modulations by doping light elements (Li^{+}, Na^{+}, Be^{2+}, Mg^{2+}) and $3d$ transition-metal (TM) elements (Mn^{2+}, Fe^{2+}, Zn^{2+}) are investigated. The composition of cation dopant X is fixed to 12.5%, namely, $X_{0.125}Ni_{0.875}O$. We calculate exchange constant and magnetic anisotropy for pure and cation-doped NiO by using first-principles calculations [2] and evaluate H_{E} and H_{A} from these properties to deduce ω_r. For the magnetic anisotropy, two contributions of the magnetic dipole-dipole interaction induced anisotropy (MDIA) and spin-orbit-coupling induced magnetocrystalline anisotropy (MCA) are treated separately. The calculations for pure NiO show that the ω_r is 1.20 THz, where the H_{E} contributes dominantly compared to the H_{A}. The ω_r value is in good agreement with the experiment [1]. When the Li^{+} is doped, the minimum value of $\omega_r \sim 0.77$ THz is obtained, which is approximately the half value of pure NiO. This reduction of ω_r is attributed to the exchange interaction of second-neighbour Ni-Ni sites, reduced by hole doping with monovalent Li^{+}. On the other hand, doping $3d$ TM cations varies the ω_r depending on the cation species. When doping Mn^{2+}, the MDIA is enhanced slightly by local spin moment of 5 μ_{B} at Mn site, but the ω_r is less affected and rather comparable to that of pure NiO. We emphasize that the maximum value of ω_r, ~ 1.60 THz, is confirmed by doping Fe^{2+}. The significant contribution of MCA preferring magnetic easy axis along $[11\bar{2}]$ is observed [3]. In our presentation, we will show systematical results of exchange interaction, MDIA, and MCA, and discuss the physical origins behind these modulated magnetic properties, including other cation dopants. The chemical trend of ω_r will be also presented.

This work is supported partly by JSPS KAKENHI (Grant numbers JP22K14290, JP21K03444, JP21H04562, and JP19K03716) and JST PRESTO (Grant number JPMJPR20B9).

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Coherent and dissipative magnetoelastic coupling in a Fe(10nm)/Py(10nm) nanowire array

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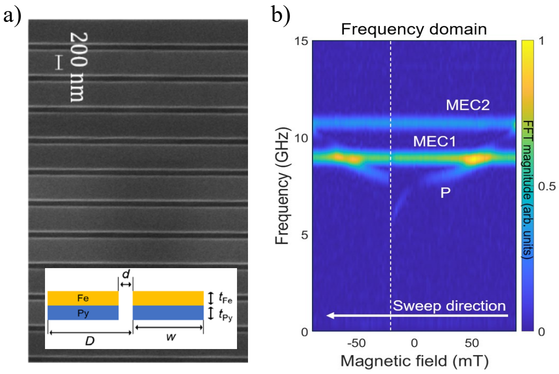

Figure 1 a) SEM micrograph of the nanowires. Inset: scheme of the sample structure, specifically in our sample D=410 nm, d=70 nm, w=340 nm and tFe=tPy=10 nm b) FFT of the tr-MOKE traces showing the three modes and a possible hybridization.

Nowadays, the control of coherent collective spin excitations in magnetically ordered materials at the nanoscale is one of the most promising concepts for the development of novel and energy-efficient information technologies. A powerful approach to manipulate spin waves is to exploit the hybridization of magnons with phonons [1]. We report on the hybrid magneto-mechanical properties of a 1D magnonic crystal composed of Fe(10 nm)/Py(10 nm) bilayered nanowires on a Si substrate, as shown in Fig. 1.a [2]. An infrared laser pulse triggers both acoustic and spin waves, and the system behaves as a magneto-mechanical cavity when an external magnetic field is properly tuned. We investigate the magneto-elastic coupling by analysis of time-resolved (tr) reflectivity and tr-MOKE. We observe two non-dispersive magnetoelastic (MEC) modes and a purely magnetic (PM) one, as shown in Fig 1.b. Complementary tr-Reflectivity and Brillouin light scattering measurements and micromagnetic simulations allowed the assignment of the MECs and PM modes. Additionally, we demonstrate how a time-resolved analysis reveals fine details of the PM-MEC1 crossing, providing evidence of the simultaneous existence of both coherent and dissipative coupling. These results could be the starting point for further studies focused on understanding what are the experimental parameters that tune such properties, which could be valuable for potential applications.

Acknowledgements

Research at IOM-CNR has been funded by the European Union - NFFA-Europe-Pilot under H2020 grant agreement n. 101007417 and NextGenerationEU under the Italian Ministry of University and Research (MUR) National Innovation Ecosystem grant ECS00000041 - VITALITY. CUP: B43C22000470005

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Time-domain measurement of hybrid magnonic system based on superconducting microwave circuit

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Hybrid magnonic systems, based on a coherent coupling between magnons and various excitations such as photons and phonons, have emerged as promising platforms for exploring novel physical phenomena and for developing an interface of quantum information processing [1]. Here, we present a real-time measurement and control of magnon interference of the hybrid magnonic system based on a superconducting microwave resonator circuit. A remote magnon-magnon coupling between two Yttrium Iron Garnet (YIG) spheres mounted 12 mm apart on a Si substrate is mediated by magnon-photon couplings between magnon modes of the YIG spheres and a microwave photon mode of a shared superconducting Niobium nitride (NbN) coplanar waveguide resonator fabricated on the same substrate [2]. Two superconducting ring antennae are placed next to each YIG sphere to excite and detect the magnon amplitude. By injecting a few nanoseconds microwave pulse to one of the antennae and tracing the real-time voltage induced to the other antenna, we observed the Rabi-like oscillation between the two YIG spheres, with a period of 35 ns, which corresponds to the magnon-magnon coupling strength of 28 MHz. We also injected multiple pulses with changing carrier frequency and delay time, and we observed a Ramsey-like interference of magnon excitations, which enabled us to dynamically program the normal mode states of the hybrid system [3]. These results offer novel controllability in hybrid magnonic systems and insights into quantum-compatible coherent information processing using magnon.

Acknowledgement

Work at Argonne and UIUC was supported by the U.S. DOE, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division under contract No. DE-SC0022060. Use of the Center for Nanoscale Materials (CNM), an Office of Science user facility, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract no. DE-AC02-06CH11357. K.-J. K. and M. S. are supported by the Technology Innovation Program (or Industrial Strategic Technology Development Program) (20020286) funded by the Ministry of Trade, Industry and Energy (MOTIE, Korea).

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Modelling non-collinear parametric pumping of forward volume spin waves by surface acoustic waves

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Parametric pumping by acoustic waves is a promising way to amplify spin waves in yttrium iron garnet (YIG) and other magnetostrictive materials to enable non-linear signal processing applications, such as frequency conversion and microwave signal correlation, in compact form factor. We present a micromagnetic simulation study, using MuMax software [1], of parametric pumping of forward volume spin waves by surface acoustic waves in YIG thin films. The acoustic wave or pump is modelled as a time- and space-periodic strain corresponding to a Rayleigh wave, which interacts with the signal spin wave through magneto-elastic coupling. The pump frequency is twice the frequency of the signal spin wave. The simulations show the amplification of the signal spin wave and the generation of the idler spin wave (Fig. 1 [left]) in accordance with conservation of energy and momentum:

$$\omega_p = \omega_s + \omega_i \quad (1)$$

$$\boldsymbol{k}_p = \boldsymbol{k}_s + \boldsymbol{k}_i, \quad (2)$$

where the symbols ω and $\boldsymbol{k}$ stand for frequency and wavevector and the subscripts *p, s,* and *i* denote pump, signal, and idler respectively. Further, the signal amplification depends on the angle between the acoustic wave and the signal spin wave as seen in Fig. 1 (right). Here, the pumping strain amplitude is plotted as an equivalent magnetoelastic field. Crucially, above ~35° incidence, the threshold for achieving signal gain falls below the pump amplitude that results in uncontrolled amplification of spin waves from the thermal bath, allowing for continuous pumping and amplification.

These results demonstrate the practicality of acoustically pumped amplification of spin waves and will serve to guide future experiments and device designs.

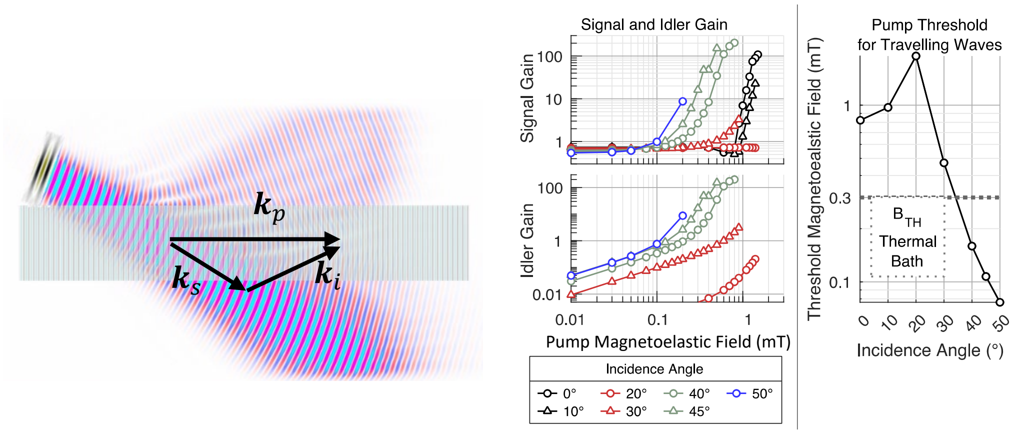

Figure 1. (left) Micromagnetic simulation of a beam of spin waves with wave vector $\boldsymbol{k}_s$, parametrically pumped by a surface acoustic wave with wave vector $\boldsymbol{k}_p$ resulting in an idler wave with wave vector $\boldsymbol{k}_i$. (right) Gain in the signal spin wave and idler as a function of the incidence angle and strength of the acoustic pump. The threshold for achieving signal gain varies with incident angle.

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Proximity effects in magnetic/superconductor epitaxial heterostructures with magnetic noncollinearity

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The proximity effect at an interface between a thin film superconductor (S) and a ferromagnet (F) is sensitively-dependent on fundamental processes such as Andreev reflection as well as the magnetic-configuration (orientation, domains, domain walls) and structural properties. In a F/S heterostructure, the magnetic exchange field from the collinear F suppresses superconductivity (short range proximity effect). Conversely, magnetic noncollinearity (MNC) can restore superconductivity, enhancing the critical temperature (T_c) in F/S/F spin valves with an antiparallel-magnetisation-alignment [1] and S/F bilayers with misoriented magnetic domains [2]. The MNC at a F/S interface can also lead to a reduction in T_c [3] through the generation of spin-aligned triplet Cooper pairs and their long-range leakage from S into F [4] (long-range proximity effect).

To further investigate the role of MNC in these proximity effects, we have undertaken a study based on epitaxial hybrid structures involving rare earth elements. These later present magnetic modulated phases that are a natural source of MNC to promote triplet components [5] and a strong orbital moment that could lead to enhanced spin switch effects [6]. Epitaxial systems are moreover powerful levels to control their magnetic phases via dimension, strains, alloying, etc [7]. We focus here on epitaxially grown F(50nm)/Nb(30nm) structures, where F is a pure Ho film, a Ho-based alloy (with Lu or Tb), or a Ho-based superlattice. The temperature and field stability of the magnetic phases, more specifically in the vicinity of the Nb superconducting transition, are investigated by SQUID. Transport measurements are carried out to study the superconductivity dependence on the magnetic order, both under zero field for different remanent states, and under field in comparing increasing and decreasing field branches.

Tc appears to be significantly affected by changes in the magnetic state. Interestingly depending on the system, the development of MNC observed by SQUID out of the saturated state generates either an increase (up to 180mK) or a decrease (up to 110mK) of T_c. Such a decrease in T_c could be a hint of long-range triplet component. We will discuss how the nature and characteristics of the MNC could explain its influence on both short and long range proximity effects. Exploring these effects in systems with MNC is vital to aid theory towards improved modelling and to develop superconducting spintronic devices.

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25th International Colloquium on
Magnetic Films and Surfaces
(ICMFS2024)
Perugia, from 7 to 12 July 2024

Posters

25th International Colloquium on Magnetic Films and Surfaces (ICMFS2024)

7 - 12 July 2024, Perugia, Italy

ICMFS2024

Poster Session - I, Monday July 8, 14:15 - 15:45

Chairs	***Yoshishige Suzuki*** ***Cristopher Marrows*** ***Dirk Grundler*** ***Oksana Koplak***
Monday Novel **A** **POSTER CODE**	**Novel functional materials and magnetic ordering phenomena - Presenting Author - Poster title**
MA 1	***Alexander Chizhik -*** *University of Basque Country, Spain- "Diversity of surface magnetic structures in composite cylindrical microwires. Magneto-optical study"*
MA 2	***Hiroki Koizumi -*** *Tohoku University, Japan - "Quadrupole anomalous Hall effect in NiCo2O4 thin films by cluster magnetic toroidal quadrupole "*
MA 3	***Wen-Chin Lin*** *- Department of Physics, National Taiwan Normal University, Taiwan - "Hydrogenation Effect on Antisymmetric Magnetoresistance in Co/Pd Multilayers "*
MA 4	***Iryna Lukiienko*** *- Brno University of Technology, Czech Republic - "Controllable magnetostriction of FeTb/Fe multilayers via the Fe sublayers"*
MA 5	***Takahiro Maeda*** *- Osaka University, Japan - "Reservoir computing with magnetic wire based on magnetic domain wall logic"*
MA 6	***Andrea Morales*** *- CTO - QZabre Ltd, Switzerland - "Recent progress in scanning NV magnetometry for nanoscale imaging and failure analysis"*
MA 7	***Goichi Narita*** *- University of Hyogo, Japan - "Enhancement of parity-check capacity by generating recurrent information flow in double lambda-shape patterned nanowire"*
MA 8	***Hikaru Nomura -*** *Tohoku University, Japan - "Short-term memory and parity check capacities of patterned magnetic wire driven by rotating magnetic field"*
MA 9	***Jing Qi*** *- University of Wuerzburg, Germany - " Structure-property relationship of reversible magnetic chirality tuning"*
MA 10	***Jimena Soler -*** *ICMM - CSIC, Spain -"Temperature dependence of coercivity in perpendicular anisotropy PrFeB film"*
MA 11	***Kazuya Suzuki*** *- Japan Atomic Energy Agency, Japan - "Tuning of spin-dependent transport properties in ferromagnetic high-entropy alloy thin films incorporating heavy metal "*
MA 12	***Milad Takhsha*** *- CNR - IMEM, Italy - "Martensite enabled magnetic flexibility of shape-memory Heuslers by microstructure engineering "*
MA 13	***Kenji Tanabe*** *- Toyota Technological Institute, Japan -" Anomalous Nernst effect in GdCo alloys for heat flux sensing"*
MA 14	***Takuya Tsujimoto -*** *Nagoya University, Japan - " Anomalous Nernst effect in nanoporous Co thin films "*
MA 15	***Marek Wójcik*** *- Institute of Physics, PAS, Poland- "Temperature-induced magnetic differentiation of equivalent Mn lattice sites in the epitaxial Mn2GaC film monitored by NMR"*
Monday Topological **B** **POSTER CODE**	**Topological Spin textures - Presenting Author - Poster title**
MB 1	***Adam Cahaya -*** *Universitas Indonesia, Indonesia - "Interplay of dipolar and Dzyaloshinskii–Moriya interactions in helicity control of hybrid magnetic skyrmion "*
MB 2	***Rintaro Eto*** *- Waseda University, Japan - " Spin-wave modes and real-space topology in the quadruple-Q magnetic hedgehog lattices"*
MB 3	***Lucia Malucelli -*** *SPINTEC, France - "Towards a skyrmion-based magnetic field sensor"*
MB 4	***Pietro Micaletti*** *- University of Ferrara, Italy- " Microstate, geometry and their footprints in dynamic spin wave properties in artificial spin ice"*
MB 5	***Felix Nickel -*** *University of Kiel Germany - "Coupling of the triple-Q state to the atomic lattice by anisotropic symmetric exchange"*
MB 6	***Masashi Shiraishi -*** *Kyoto University, Japan* ***- "*** *Detection of ferroic Berry curvature dipole in a topological crystalline insulator, PbSnTe"*
MB 7	***Wulf Wulfhekel*** *- Karlsruhe Institute of Technology , Germany -" Observation of the sliding phason mode of the incommensurate magnetic texture in Fe/Ir(111)"*
Monday Theory **C** **POSTER CODE**	**Theory and modeling of films and surfaces - Presenting Author - Poster title**
MC 1	***Haoran Chen -*** *Fudan University, China- " Six-fold angular-dependent magnetoresistance in four-fold Fe (001) films"*
MC 2	***Uladzislau Makartsou -*** *Adam Mickiewicz University, Poland - " Experimental and Numerical Demonstration of Spin-Wave Self-Imaging in YIG film "*

25th International Colloquium on Magnetic Films and Surfaces (ICMFS2024)

7 - 12 July 2024, Perugia, Italy

ICMFS2024

Poster Session - II, Wednesday July 10, 14:15 - 15:45

Chairs	***Yoshishige Suzuki*** ***Cristopher Marrows*** ***Dirk Grundler*** ***Oksana Koplak***

Wednesday Advanced **A** **POSTER CODE**	**Advanced synthesis and characterization (imaging, spectroscopy, etc.) of films and surfaces - Presenting Author - Poster title**
WA 1	***Peter Bencok -*** *Diamond Light Source,UK - "Electromagnet end station for x-ray magnetic circular dichroism"*
WA 2	***Bohdana Blyzniuk -*** *Jerzy Haber Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Poland - "CTrue resistivity in magnetite epitaxial ultra-thin films "*
WA 3	***Ida Breivik -*** *Norwegian University of Science and Technology, Norway - "Tuning the angular dependence of the switching field of thin film nanomagnets"*
WA 4	***Fathoni Kresna Bondan -*** *National Institute for Materials Science, Japan - "CoPd-based perpendicular synthetic antiferromagnetic layers with strong exchange coupling oscillation"*
WA 5	***Amalio Fernandez-Pacheco -*** *Vienna University of Technology, Austria - "Geometric-magnetic chirality coupling in double-helix nanostructures"*
WA 6	***Ewa Jedryka -*** *Institute of Physics, Polish Academy of Sciences, Poland - "Effect of Si substitution on the local magnetic properties of the Mn5(Ge1-xSix)3 /Ge(111) epitaxial films"*
WA 7	***Natalia Kwiatek -*** *SOLARIS National Synchrotron Radiation Centre, Krakow, Poland - "Correlations of chemical and magnetic properties in cobalt/magnetite and cobalt/hematite epitaxial heterostructures"*
WA 8	***Jia Lu -*** *Univ of S. California, USA - "Co and Co/Cu dual-segment nanowires "*
WA 9	***Shyni Punathum Chalil -*** *CNR - IOM, Italy - "Electrical and magnetic properties of Fe_3O_4 thin films deposited via 1st harmonic Nd:YAG laser"*
WA 10	***Haruto Seki -*** *Chiba University, Japan - "STM/STS study of ultrathin MnTe monolayer films on Fe(001) combined with DFT calculation"*
WA 11	***Smibin Shaju -*** *Jerzy Haber Institute Of Catalysis And Surface Chemistry - Polish Academy of Sciences, Poland - "Magnetic properties of the epitaxial thin films of Fe_xSn_y "*
WA 12	***Sylvain Eimer*** *- National Key Lab of Spintronics, Hangzhou, China - "Effect of helium ion irradiation on spintronic multilayers thin films stacks under different substrates"*
WA 13	***Wang Hanchen*** *- ETH Zurich, Switzerland - "Understanding the magnetic properties of ultrathin BiYIG grown by sputtering"*
WA 16	***Alexander Klasen*** *- Park Systems Europe GmbH, Germany - "Investigating Magnetic Materials on the nm Scale Using Atomic Force Microscopy"*

Wednesday AF SPINTRONICS **B** **POSTER CODE**	**Antiferromagnetic spintronics - Presenting Author - Poster title**
WB 1	***Toma Hattori*** *- Nagoya University, Japan - "Spin pumping modes in α-Fe_2O3/Pt bilayers"*
WB 3	***Alberto Pomar*** *- ICMAB - CSIC, Spain - "Spin injection through ferromagnet/antiferromagnet oxide heterostructures"*
WB 4	***Tong Wu*** *- Fudan University, Shanghai, China - "Interfacial Perpendicular Magnetic Anisotropy of Ultrathin Fe(001) film Grown on CoO(001) Surface"*

Wednesday 3D Magnonics **C** **POSTER CODE**	**3D Magnonics - Presenting Author - Poster title**
WC 1	***Johannes Greil*** *- Technical University of Munich, Germany - "A magnonic Rowland spectrometer using curvilinear transducers"*

Wednesday 2D **D** **POSTER CODE**	**2D and van der Waals materials - Presenting Author - Poster title**
WD 1	***Ryotaro Sano*** *- Kyoto University, Japan - "Surface acoustic waves-driven magnon spin Hall effect in atomically thin van der Waals antiferromagnets"*
WD 2	***Emma Aoustin*** *- Laboratoire Albert Fert, CNRS, Thales, France - "Towards switchable magnetic tunnel junctions based on two-dimensional polyoxometalates monolayer"*

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ICMFS2024

Poster Session - III, Thursday July 11, 14:15 - 15:45

Chairs	***Yoshishige Suzuki*** ***Cristopher Marrows*** ***Dirk Grundler*** ***Oksana Koplak***
Thursday Hybrid **A** **POSTER CODE**	**Hybrid heterostructures and magnon coupling- Presenting Author - Poster title**
TA 1	***Jinhyun Baek*** *- Korean Advanced Institute of Science and Technology, South Korea - " Wavevector-resolved electrical spectroscopy of propagating spin wave based on flip-chip technique "*
TA 2	***Luca Gnoli*** *- CNR - ISMN, Italy - "Enhancement of antiferromagnetic stability by adsorption of molecular layers "*
TA 3	***Mio Ishibashi*** *- Tohoku University, Japan - "Oscillation between acoustic and optic magnon in synthetic antiferromagnets"*
TA 4	***Tufan Roy -*** *Tohoku University, Japan - "Effects of Mn monolayer insertion in spin-transport properties of Fe/MgO/Fe and Co/MgO/Co magnetic tunnel junctions"*
TA 5	***Katrin Schultheiss*** *- Helmholtz-Zentrum Dresden-Rossendorf, Germany - "Modification of three-magnon splitting by in-plane magnetic fields "*
TA 6	***Kotaro Taga*** *- Kyoto University, Japan - "Quantitative evaluation of the coupling between spin wave and surface acoustic wave in NiFe thin films"*
TA 7	***Seiya Takano*** *- Tohoku University, Japan - "Highly sensitive tunnel magneto-resistive sensor with magnetic vortex structure"*
TA 8	***Xixiang Zhang*** *- King Abdullah University of Science & Technology, Saudi Arabia - "Reconfigurable spin current transmission and magnon–magnon coupling in hybrid ferrimagnetic insulators"*
TA 9	***Albert MIn Gyu Park*** *-Korea Advanced Institute of Science and Technology, Republic of Korea - " Geometry-dependence of magnon-phonon coupling in YIG-GGG platform "*
Thursday Ultrafast **B** **POSTER CODE**	**Ultrafast spin and magnetization dynamics- Presenting Author - Poster title**
TB 1	***Anna Giordano*** *- Università degli studi di Messina, Italy - "A micromagnetic study of the fractional resonance response driven by voltage‐controlled magnetic anisotropy"*
TB 2	***Julián Milano -*** *Instituto de Nanociencia y Nanotecnología, Argentina - "Influence of ferromagnetic coupling in Fe85Co15/Py bilayers on the ISHE voltage generated by spin pumping "*
TB 3	***Raffaele Silvani*** *- University of Perugia, Italy - "Reconfigurable magnetic devices with integrated micro-magnets"*
Thursday Multiferroics **C** **POSTER CODE**	**Multiferroics and magnetoelectric coupling - Presenting Author - Poster title**
TC 2	***Fatih Ilgaz*** *- Kiel University, Germany - " Miniaturized delta-E effect magnetoelectric sensors"*
TC 3	***Marek Przybylski -*** *AGH University of Krakow, Poland - "Current induced magnetization dynamics in multiferroic tunnel junctions "*
TC 4	***Hemanita Sharma*** *- University of Trieste, Italy - "Light-induced magnetic modifications in Ni/KNbO3 multiferroic heterostructure "*
Thursday Spin-transfer **D** **POSTER CODE**	**Spin-transfer and spin-orbit torque - Presenting Author - Poster title**
TD 1	***Adam Cahaya -*** *Universitas Indonesia, Indonesia - "Spin–orbit torque on nuclear spins via hyperfine interactions "*
TD 2	***Kuan-Chia Chiu*** *- Physics Department, National Taiwan University, Taiwan - "Enhanced spin-orbit torque efficiency with a bulk WSe2 spin sink "*
TD 3	***Shiyang Lu*** *- Beihang University, China - "Spin-orbit torque efficiency enhancement to tungsten-based SOT-MTJs by interface modification with an ultrathin MgO"*
TD 4	***Yukihiro Marui*** *- Tohoku University, Japan - "Spin and orbital Hall effects in V and Pt"*
TD 5	***Andrea Meo -*** *Politecnico di Bari, Italy - "Arrays of coupled magnetic tunnel junctions for mechanical applications "*
TD 6	***Federica Nasr*** *- ETH Zurich, Switzerland - "Spin–orbit torques and magnetization switching in Gd/Fe multilayers generated by current injection in NiCu alloys"*
TD 7	***Zhenchao Wen*** *- National Institute for Materials Science, Japan - "Spin-orbit torque driven by interfacial chemistry in topological BiSb/NiFe bilayers with Ti insertion"*
TD 8	***Shinji Yuasa*** *- National Institute of Advanced Industrial Science and Technology, Japan - "Energy-efficient SOT-MRAM writing operation using amorphous W-Ta-B as a spin Hall material"*
TD 9	***Shinji Yuasa*** *- National Institute of Advanced Industrial Science and Technology , Japan - "Enhanced annealing stability in perpendicularly magnetized magnetic tunnel junctions using an Fe-substituted MgO barrier"*

Diversity of surface magnetic structures in composite cylindrical microwires. Magneto-optical study

Alexander Chizhik[a], Arcady Zhukov[a,b]

[a] University of Basque Country, UPV/EHU, San Sebastian, Guipuzcoa, 20018, Spain
[b] IKERBASQUE, Basque Foundation for Science, Bilbao

Advances in the technological application of magnetic cylindrical glass-covered microwires have established a goal in studying magnetic properties of these composite structures [1]. The magnetostriction coefficient that determines the features of the magnetic structures has opposite signs in Fe- and Co-rich microwires. These two classes of complementary materials form the basis for a wide class of magnetic sensors. In this work, we present the classification of surface magnetic domain structures that we have established as a result of our magneto-optical Kerr effect (MOKE) studies.

The magnetic domain structures in the microwire were investigated using a high-resolution, wide-field optical polarizing microscope working in longitudinal mode (Fig.1a). The formation or the transformation of magnetic structures was observed depending on the sign of the magnetostriction constant. The samples were subjected to torsion (Fig. 1b), tension and bending stress, circular magnetic field as well as the influence of annealing. As a result, a series of images of domain structures was obtained, which was systematized. We have established that the basic structure is a helical one, which transforms into a spiral, elliptical, cylindrical or longitudinal structure.

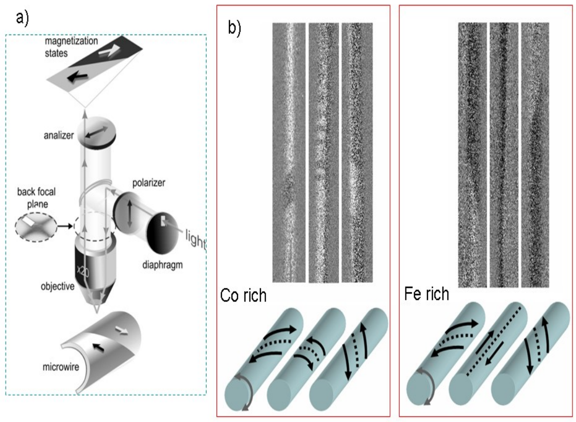

Figure 1: a) MOKE microscopy; b) images of surface domain structures in Co-rich and Fe-rich microwires.

Also we have found that different scenarios of magnetization reversal exist in magnetic microwires, and the application of external parameters can affect the mechanical, magnetic, and electrical properties and thus the practical activation of varying scenarios. The difference between the scenarios is determined particularly by the suppression or enhancement of various inclined magnetic states. It is known that a circular magnetic field produced by an electrical current flowing along the microwire can serve as a competitive tool to strengthen or weaken the effects of torsion stress. As a result, we have expanded our ability to control the transition between different magnetization reversal scenarios.

[1] P. Corte-León et al., Applied Materials Today **26** (2022), 101263.

Quadrupole anomalous Hall effect in $NiCo_2O_4$ thin films by cluster magnetic toroidal quadrupole

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[a] Tohoku University, Sendai, Japan.
[b] National Institute for Materials Science (NIMS), Tsukuba, Ibaraki, Japan.
[c] University of Tsukuba, Tsukuba, Ibaraki, Japan.

$NiCo_2O_4$ (NCO) is a conductive inverse spinel oxide which shows ferrimagnetism with a Néel temperature as high as 400 K [1]. Recently, the spin reorientation in NCO(001) films has been reported in which the magnetic anisotropy changes from perpendicular magnetic anisotropy (PMA) to easy-cone magnetic anisotropy at low temperature [2]. Then, the magnetic easy direction is tilted from perpendicular to the film plane, which is a conical shape. Since the conical shape has a degree of freedom to the in-plane direction, NCO could have a non-colinear spin texture. In this study, we investigate whether NCO has a non-colinear spin texture, by carefully measuring the Hall effect.

Firstly, we perform Hall measurements with an easy-cone state. The unconventional response is observed, implying the existence of a nontrivial spin texture by easy-cone magnetic anisotropy. Next, we investigate the applied current (***I***) direction dependence of the unconventional Hall effect. The extracted unconventional Hall signal is reversed by the 90-degree rotation, as shown in Fig. 1(a). In contrast, it disappears when ***I*** is parallel to NCO||⟨110⟩. In general, anomalous Hall effect (AHE) originated from the magnetic dipole and magnetic octupole must be independent of the current direction. Therefore, the unconventional Hall effect observed in NCO is attributed to the other nontrivial spin texture. The symmetry analysis based on the cluster magnetic multipole theory [3] indicates that the anisotropic AHE originated from an anisotropic band structure induced by the cluster magnetic toroidal quadrupole, as shown in Fig.1(b) and (c) [4].

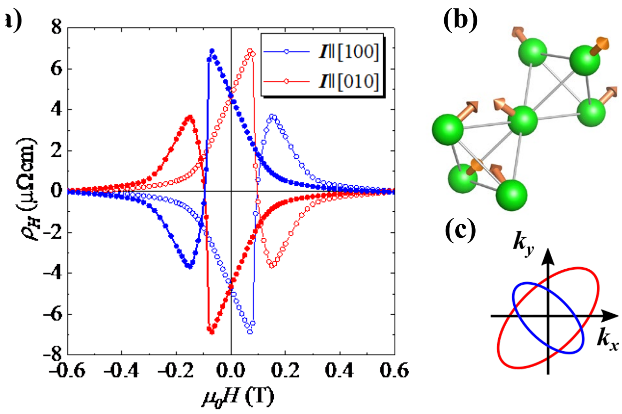

Figure 1: (a) Current direction dependence of the observed unconventional anomalous Hall effect. (b) Realized spin texture and (c) schematic band images by coexisting MTQ and magnetic dipole.

[1] X. Chen, et al., Adv. Mater. **31**, 1805260 (2019).

[2] H. Koizumi, et al., Phys. Rev. B **104**, 014422 (2021).

[3] M.-T. Suzuki, et al., Phys. Rev. B **99**, 174407 (2019).

[4] H. Koizumi et al., Nat. Commun. **14**, 8074 (2023).

Hydrogenation Effect on Antisymmetric Magnetoresistance in Co/Pd Multilayers

Wen-Chin Lin[a], Y.-R. Chu[a], C.-T. Hsieh[a], C.-M. Liu[a], J.-Y. Hong[b]

[a] Department of Physics, National Taiwan Normal University, Taipei, Taiwan
[b] Department of Physics, Tamkang University, New Taipei City, Taiwan

In Co/Pd multilayers, we observe controllable anomalous magnetoresistance (MR) influenced by the unique geometric relationship among current, magnetization, domain wall motion, and hydrogen loading. An antisymmetric MR is measured in the ambient condition, because of the presence of perpendicular magnetic anisotropy (PMA) and the asymmetric domain wall motion, as shown in Fig. 1(a)-(e). The investigation, including magnetic domain images acquired through the Magneto-Optical Kerr Microscope and transport properties measurements, attributes the antisymmetric MR to the anomalous Hall effect within the PMA sample. Upon hydrogen absorption, the magnetization becomes tilted and then turns to in-plane anisotropy. Meanwhile, the MR curve sensitively changes with slight hydrogenation, corresponding to the spin-reorientation transition process in the Co/Pd multilayer, as shown in Fig. 1(f)-(h). Upon more hydrogen exposure, an obvious MR is only present when an in-plane magnetic field is applied, signifying a transition to in-plane anisotropy. This study emphasizes the tunable nature of MR in the Co/Pd multilayer system, providing novel insights into the diversity of MR, which holds the potential to influence the multifunctionality of spintronic devices. The high sensitivity of PMA and MR behavior to a few mbar hydrogen pressure suggests its potential for application.

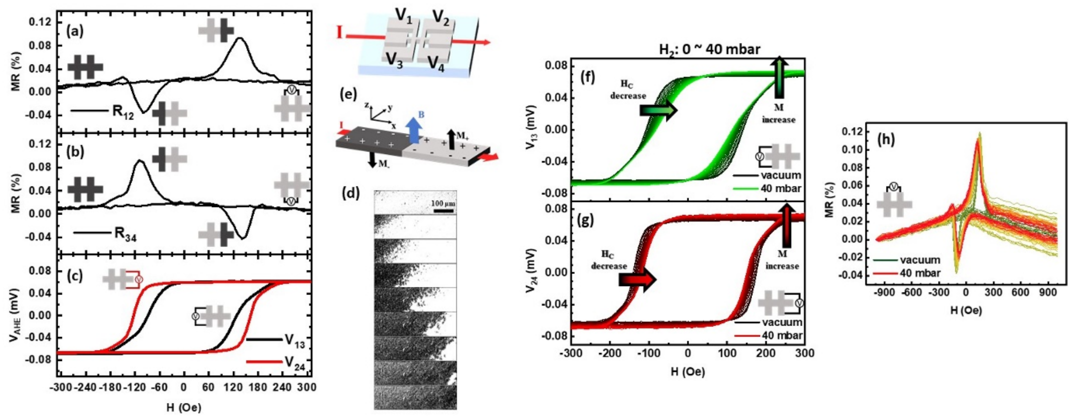

Fig. 1 (a)-(b) Asymmetry MR, (c) anomalous Hall effect, and (d) domain progression image measured with an out-of-plane magnetic field, as illustrated in (e). (f)-(g) AHE and (h) MR measured upon hydrogen loading from a vacuum to 40 mbar H_2 gas.

[1] P. C. Chang, T. H. Chuang, D. H. Wei, and W. C. Lin, Appl. Phys. Lett. 116, (2020).
[2] W. H. Wang, Y. S. Cheng, H. S. Sheu, W. C. Lin, and P. H. Jiang, Phys. Rev. B 104, 1–8 (2021).
[3] P.C. Chang et al. Scientific Reports 8:6656 (2018).

Controllable magnetostriction of FeTb/Fe multilayers via the Fe sublayers

Iryna Lukiienko, Vojtěch Uhlíř

CEITEC BUT, Brno University of Technology, Brno, Czechia

Magnetostrictive materials are widely used in different mechanic and electronic equipment as components which produce mechanical force, torque or displacement. Such kind of actuators play an important role for the development of smart modern materials and devices [1]. The majority of effective magnetostrictive materials consists of complex rare earth-based composites with Fe [2]. Their large magnetostrictive properties are provided due to antiferromagnetic exchange coupling between Fe and a rare earth element. These synthetic materials have sperimagnetic properties with giant magnetostriction (~ 10^{-3}), out-of-plane magnetic anisotropy, and high field of magnetic saturation (> 2.5 T) [2].

In this work we demonstrate the control of magnetostriction and perpendicular magnetic anisotropy in the complex multilayer system [$Fe_{0.6}Tb_{0.4}$ (4.5 nm) / Fe (x nm)]$_4$. Critical is the thickness of the Fe sub-layers, which have much weaker and opposite in sign magnetostrictive properties than the FeTb sub-layers. Magnetooptical Kerr effect measurements have shown that the separate $Fe_{0.6}Tb_{0.4}$ (4.5nm) film is Tb-dominant and its average sperimagnetic moment doesn't lay in the film plane at room temperature. In the case of the composite [$Fe_{0.6}Tb_{0.4}$ (4.5nm) / Fe]$_4$ with thin Fe sub-layers, magnetic moments in the FeTb alloy orient out-of-plane even at low temperatures (300 – 60K) due to antiferromagnetic Fe-Tb exchange coupling on top and due to ferromagnetic Fe-Fe exchange coupling at the bottom of each FeTb layer. Increase of the Fe sub-layer thickness enhances in-plane magnetic anisotropy in the FeTb alloy layers and enhances their magnetostrictive properties (fig. 1). Moreover, in accordance with [3], the saturating magnetic field of the multilayer system under study is several times smaller than that for the FeTb alloy film, thus enhancing its applicability range.

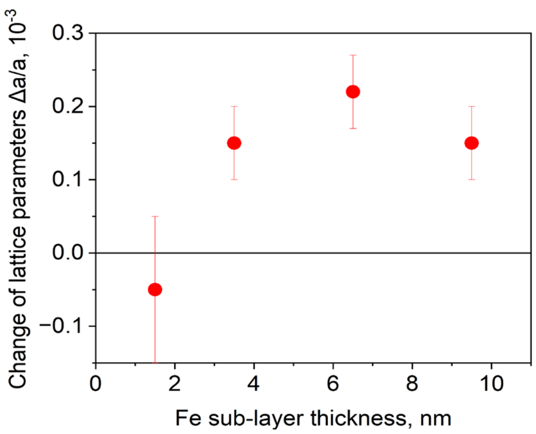

Figure 1: Change of lattice parameters of the multilayers Fe(epit)/[FeTb/Fe]$_4$ versus the Fe sub-layer thickness (after subtraction of the contribution from the Fe epitaxial layer).

[1] X. Liang, C. Dong, H. Chen, J. Wang, Y. Wei, M. Zaeimbashi, Y. He, A. Matyushov, C. Sun, and N. Sun. Sensors **20** (2020), 1532, https://doi.org/10.3390/s20051532.

[2] A. Clark, H. Belson, Phys. Rev. B **5** (1972), 3642–3644.

[3] E. Quandt, A. Ludwig, J. Mencik, and E. Nold, J. Alloy and Comp. **258** (1997), 133-137.

Reservoir computing with magnetic wire based on magnetic domain wall logic

Takahiro Maeda[a], Hitoshi Kubota[b], Soma Miki[a,c,d], Minori Goto[a,c,d], Yoshishige Suzuki[a,c,d], Hikaru Nomura[a,c-e]

[a] Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka, Japan
[b] National Institute of Advanced Industrial Science and Technology (AIST)
[c] Center for Spintronics Research Network (CSRN), Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka, Japan
[d] Spintronics Research Network Division, Institute for Open and Transdisciplinary Research Initiatives, Osaka University, Suita, Osaka,, Japan
[e] International Center for Synchrotron Radiation Innovation Smart, Tohoku University, Sendai, Miyagi, Japan

Recently, various physical reservoirs have been proposed to reduce power consumption in neural networks[1]. As a physical reservoir, we have proposed the use of magnetic domain wall logic device structures. Using micromagnetic simulations, we have shown that reservoir computing is possible by using the magnetization state of the domain wall logic device structure as a node[2]. This domain wall logic-based reservoir exhibits nonlinear computing capability in a small footprint, in addition to the non-volatility of information and computing power of domain wall logic devices. However, its experimental demonstration has not been performed yet. Therefore, in this study, we evaluate the reservoir computing performance using a reservoir based on domain wall logic devices.

We fabricated magnetic wire of Ta(5 nm)/Ni-Fe(20 nm)/Ta(5 nm) on SiO2/Si substrate. Fig. 1 shows a MOKE (magneto-optical Kerr effect) microscope image of our reservoir. Magnetic domain walls were written with the magnetic field generated by a square-wave current applied through the upper electrode shown in the left-hand side of the Fig. 1. This allowed a binary input of 0 and 1 depending on the current direction. As in a domain wall logic device[3], we also use a rotating external magnetic field to drive the domain wall in the magnetic wires. The magnetic state of the wires were measured using MOKE microscope as node states. To evaluate a performance of the reservoir, we use short term memory task and parity check task. In the presentation, we will show the detail results of our reservoir performance.

This research was partly supported by received partial support from JSPS KAKENHI Grant No. 20H05655, JAPAN, and JST CREST Grant No. JPMJCR20C6, JAPAN.

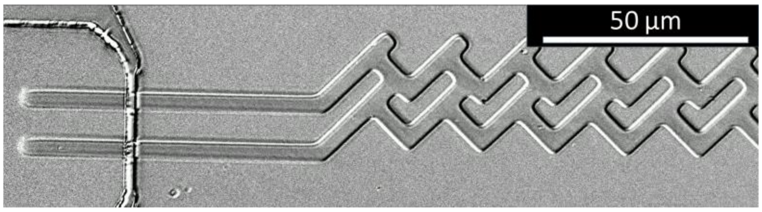

Fig. 1 MOKE image of our resoervoir
based on magnetic domain wall logic device.

1. G. Tanaka, T. Yamane, J. B. Héroux, R. Nakane, N. Kanazawa, S. Takeda, H. Numata, D. Nakano and A. Hirose, Neural Networks **115**, 100-123 (2019).
2. K. Hon, K. Takahashi, K. Enju, M. Goto, Y. Suzuki and H. Nomura, Applied Physics Letters **120** (2) (2022).
3. D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit and R. P. Cowburn, Science **309** (5741), 1688-1692 (2005).

Recent progress in scanning NV magnetometry for nanoscale imaging and failure analysis

Andrea Morales[a], Björn Josteinsson[a], Simon Josephy[a], Jan Rhensius[a] Gabriel Puebla-Hellmann[a]

[a] Qzabre Ltd, Regina-Kägi-Strasse 11, 8050, Zurich, Switzerland

Scanning NV, where a single defect in diamond is used as an atomic scale field sensor, is seeing increased adoption for imaging weak magnetic fields at the nanometer scale. The capabilities of the NV as a sensor, however, offer much more than the quantitative mapping of even sub uT fields which we demonstrate. After giving an overview of recent progress of NV magnetometry to image antiferromagnetic [1], topological spin textures as well as weak magnetic fields [2], I will then discuss novel applications that go beyond conventional magnetometry. Here other NV properties are exploited to acquire information on magnetic hysteresis at the nanoscale as well as to capture ferromagnetic resonance (FMR) as a function of field amplitude, direction and sample surface location or to perform failure analysis on nanoscale devices. I will also briefly give an update on the state of commercial NV magnetometry at low temperatures down to a few Kelvin.

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[1] P.Welter et al, Phys. Rev. Applied 19, 034003

[2] W.S. Huxter et al, Nature Communication 13, 3761 (2022)

Enhancement of parity-check capacity by generating recurrent information flow in double lambda-shape patterned nanowire

Goichi Narita[a], Teijiro Isokawa [a], Hikaru Nomura[b],
Hitoshi Kubota[c], Tomohiro Taniguchi[c], Naotake Kamiura [a]

[a] University of Hyogo, Hyogo, Japan
[b] Tohoku University, Miyagi, Japan
[c] National Institute of Advanced Industrial Science and Technology, Ibaraki, Japan

Physical reservoir computing has been investigated in various kinds of magnetic structures [1-4]. We examined a patterned nanowire with lambda-shape structure as a reservoir, in which information can be transferred in one direction [5]. The reservoir shows a high short-term memory (STM) capacity, which quantifies the amount of data the reservoir recognizes as it is. However, parity-check (PC) capacity in the reservoir, which corresponds to a non-linear computing capability, was found to be low. The PC capacity quantifies the ability to estimate a correlation between past and present data and is required for XOR operation. A possible solution to enhance the PC capacity is to introduce a structure of recurrent information flow, which mixes the past and present data to correlate between each other.

In this work, we propose a patterned nanowire reservoir consisting of two lambda-shape nanowires as schematically shown in Fig. 1(a), which have opposite directions of information flow. Time-series data are inputted from the input area as magnetic domain walls and flow in the nanowire by applying rotating magnetic field. The domain wall motion was calculated by using Mumax3. We found that the presence of two nanowires generates a recurrent flow of information, which was absent in the previous reservoir [5]. The recurrent flow of the information naturally results in the correlation between past and present data. This can be confirmed by evaluating squared-correlation coefficients. Compared with the previous works [Fig. 1(b), left], the present system shows a longer correlation for PC capacity [Fig. 1(b), right]. As a result, the PC capacity higher than the previous work is obtained in the present structure. These results revealed the relationship between the flow of the domain wall motion and the information processing capacity and indicate a future direction for further improvement of the computational ability. This work was supported by JSPS KAKENHI Grant Number 20H05655.

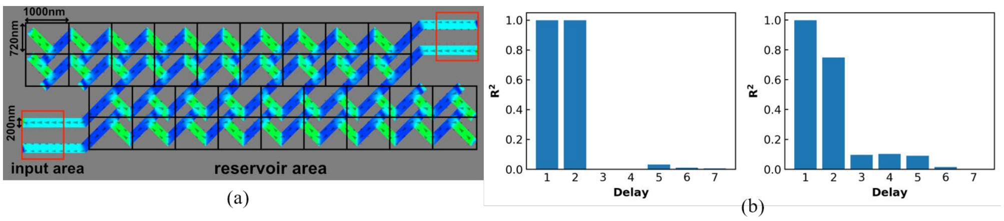

Figure 1: (a) Schematic illustration of the proposed double lambda-shape patterned nanowire reservoir. (b) Squared-correlations for the PC capacity. The left and right are those for the conventional [4] and present works, respectively. The horizontal axis is delay, which characterizes the distance between two correlated data.

[1] J. Torrejon et al., Nature 547, 428 (2017).

[2] G. Bourianoff et al., AIP Adv. 8, 055602 (2018).

[3] S. Watt and M. Kostylev, Phys. Rev. Applied 13, 034057 (2020).

[4] K. Hon et al., Appl. Phys. Express 14, 033001 (2021).

[5] K. Hon et al., Appl. Phys. Lett. 120, 022404 (2022).

Short-term memory and parity check capacities of patterned magnetic wire driven by rotating magnetic field

Kohei Enju[a], Takahiro Maeda[a], Soma Miki[a,b],
Minori Goto[a,b], Yoshishige Suzuki[a,b] and Hikaru Nomura[a,b,c]

[a]Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka, Japan
[b]enter for Spintronics Research Network, Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka, Japan
[c]International Center for Synchrotron Radiation Innovation Smart, Tohoku University, Sendai, Miyagi, Japan

In recent years, various reservoirs using physical phenomena have been studied[1]. Among them, reservoirs using magnetic materials can take advantage of the non-volatility and computing power of information possessed by magnetic materials. Domain wall logic[2] and nanomagnet logic[3] have been proposed as logic operation elements using magnetic materials. In these devices, information is stored using a magnetization direction, and logic operations are realized by switching the magnetization state. Various elements such as NOT gates and AND gates have been proposed. Recently, we have shown that reservoir computing can be performed by using the magnetization state of magnetic wires in domain wall logic as a reservoir through numerical simulations[4]. We have found that the domain wall logic structure with short term memory capability can be extended to nonlinear computing by using the reservoir computing. However, experimental demonstration of this capability has not been performed yet.

In this study, we used patterned magnetic wires to evaluate the memory and nonlinear computing capability of the device. Fig. 1 shows an optical microscope image of a reservoir fabricated by photolithography. The reservoir consists of thin Ni-20at.%Fe wires with a thickness of 15 nm and a line width of about 2 um. The magnetization state of the magnetic wires was used as node state. The magnetization states were acquired using a magneto-optical Kerr effect (MOKE) microscope. An elliptical rotating magnetic field generated by a two-axis electromagnet was used to drive the magnetic wall. Zeros and ones of binary information were input by varying the long and short radius of the rotating magnetic field. As a result of trained short term memory task and parity check task, we confirmed that the STM capacity and PC capacity increased by using this reservoir compared to case where the teacher data was directly used as the node state. From these results, we confirmed that the use of magnetic wires as a reservoir can provide non-linear computational capacity. By optimizing the structure of the magnetic wire, we expect to realize a reservoir that can be used for various tasks.

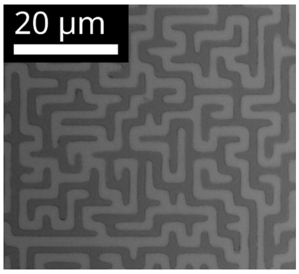

Fig. 1 optical microscope image of a magnetic wire reservoir.

This research was partly supported by received partial support from JSPS KAKENHI Grant No. 20H05655, JAPAN, and JST CREST Grant No. JPMJCR20C6, JAPAN.

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Structure-property relationship of reversible magnetic chirality tuning

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The Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction mediates collinear magnetic interactions via the conduction electrons of a nonmagnetic spacer, resulting in a ferro- or antiferromagnetic magnetization in magnetic multilayers. Recently it has been discovered that heavy nonmagnetic spacers are able to mediate an indirect magnetic coupling that is noncollinear and chiral [1]. This Dzyaloshinskii-Moriya-enhanced RKKY interaction causes the emergence of a variety of interesting magnetic structures, such as skyrmions and spin spirals. In this talk/poster, I present the results by spin-polarized scanning tunnelling microscopy that the interchain coupling between manganese oxide chains on Ir(001) can reproducibly be switched from chiral to collinear antiferromagnetic by increasing the oxidation state of MnO_2, while the reverse process can be induced by thermal reduction [2]. The underlying structure–property relationship is revealed by low-energy electron diffraction intensity analysis (LEED-IV). Density functional theory calculations suggest that the magnetic transition may be caused by a significant increase of the Heisenberg exchange which overrides the Dzyaloshinskii-Moriya interaction upon oxidation.

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Temperature dependence of coercivity in perpendicular anisotropy PrFeB film

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Perpendicular anisotropy thin, magnetic films exhibiting large coercivities have a relevant research interest from the standpoint of the implementation of spin transfer torque magnetic random-access memories [1]. In this work we report on the thermal dependence of the magnetization reversal processes observed on PrFeB thin films having a thickness of 60 nm. The samples were prepared by DC magnetron sputtering onto Si(001)/Mo substrates held during deposition at a temperature of 870 K and subsequently annealed at 1020 K for 15 minutes. Figure 1a shows the saturated hysteresis loops measured, at room temperature, on a SQUID magnetometer along the out-of-plane (oop) direction, for three different sample azimuthal orientations. The indistinguishable loops shown are associated to a well-defined perpendicular to the film plane global easy axis plausibly due to a well-defined, 2:14-1 phase, c-axis texture. They also evidence both the occurrence of a low field demagnetizing process, related to secondary phases, and that of a high demagnetizing field reversal processes taking place from 1.0 T to 2.2 T. Moreover, the high coercivity values observed indicate a reasonable exchange isolation of the hard phase grains, most likely related to a Pr-rich composition of the film with respect to the 2:14:1 phase (a ratio Fe/Pr(film) = 3 vs Fe/Pr(2:14:1) = 7) as characterized by HR-TEM and EDX. The maxima of the differential susceptibility (identified with the average field hard phase reversal, H_c) have been estimated from the demagnetization branches of the hysteresis loops measured from 350 K down to 50 K by VSM under a maximum field of 9 T. Our data have been discussed in terms of the Kronmüller coercivity model [2] (Figure 1b), which demonstrates the excellent crystallinity of the hard magnetic phase.

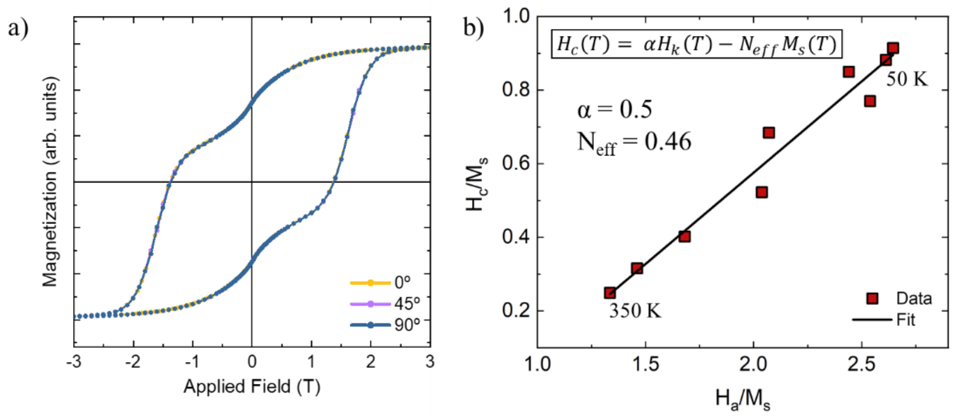

Figure 1: a) Oop hysteresis loops measured at different azimuthal angles and b) χ_d/M_s vs. H_a/M_s fit according to Kronmüller coercivity model.

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Tuning of spin-dependent transport properties in ferromagnetic high-entropy alloy thin films incorporating heavy metal

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High-entropy alloys (HEAs) have attracted considerable attention because of their excellent mechanical, heat-, corrosion-, and irradiation-resistance properties. Most studies have focused on their applications as structural materials. However, ferromagnetic HEAs may also exhibit excellent electromagnetic functions which are not observed in conventional alloys. In particular, new applications of HEAs are expected to develop by applying the fabrication method of highly structure-controlled nanolayered thin films, which is a specialty in the spintronics field. We focused on FeNiCoCuPd HEAs[1], which exhibit Curie temperatures higher than room temperature and contain Pd as a heavy metal with a large spin-orbit interaction In this study, we report the spin-dependent transport properties of FeNiCoCuPd thin films fabricated using a co-sputtering method. The thin films were deposited using an ultrahigh vacuum sputtering system equipped with an 8-way cathode (base pressure of ~10^{-7} Pa). The stacking structure of a thermally oxidized Si substrate/ $Fe_{20}Ni_{20}Co_{20}Cu_{20-x}Pd_x$ (30 nm, $0<x<10$)/Ta(3 nm, as a capping layer) was prepared by co-sputtering $Fe_{50}Co_{50}$, Ni, Cu, and Pd targets at a controlled output in each cathode. The structural and magnetic properties of the thin-film samples were evaluated using XRD and VSM measurements. Hall bar devices for evaluation of anisotropic magnetoresistance effect (AMR), anomalous Hall effect (AHE) were fabricated by conventional photolithography and Ar milling process. Figure 1 shows the XRD profiles of $Fe_{20}Ni_{20}Co_{20}Cu_{30}Pd_{10}$, $Fe_{20}Ni_{20}Co_{20}Cu_{20}Pd_{20}$, and $Fe_{20}Ni_{20}Co_{20}Cu_{10}Pd_{30}$ thin films. All the samples showed a single-phase fcc texture with a mostly 111 orientation. Magnetic measurements revealed that all films exhibited ferromagnetic hysteresis with in-plane magnetization. Figure 2 shows the dependence of the AMR effect on the Pd content measured at room temperature, which shows a tendency to increase in proportion to the Pd content in the thin film. These results suggest that the spin-dependent transport properties of ferromagnetic HEA thin films can be tuned by heavy elements. This research was partly supported by the JSPS Grants-in-Aid for Scientific Research 21K18180.

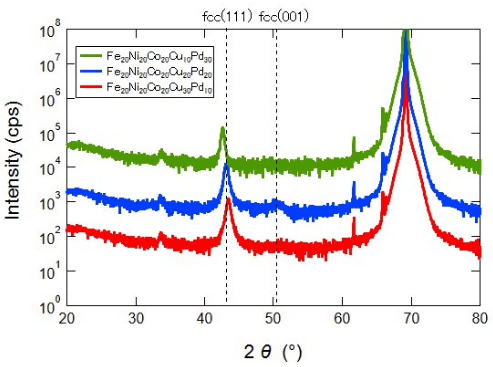

Figure1 XRD profiles of HEA films with different compositions.

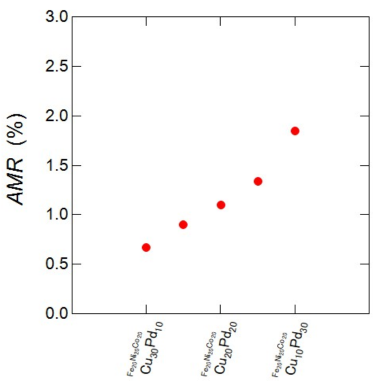

Figure2 Composition dependence of AMR ratio at 300 K

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Martensite enabled magnetic flexibility of shape-memory Heuslers by microstructure engineering

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Magnetic shape-memory (MSM) Heuslers show strong coupling between magnetic and structural degrees of freedom, evidencing correlation between magnetic, thermal and mechanical characteristics of the material through a magnetostructural phase transformation. In particular, MSM Heusler thin films are of special interest due to possible integration in smart micro/nanodevices such as sensors, energy harvesters and actuators. Recently, successful epitaxial growth of MSM Heusler thin films on silicon substrates using $SrTiO_3$ buffer layer has facilitated integrating these materials into micro/nanoelectronics and micro/nanomachining technology based on silicon [1].

The ability to control the microstructure, which rules out the magnetic characteristics of these films at different length scales, is the key point for the optimization of their magnetic functional properties. Upon temperature variation, Ni-Mn-Ga films undergo phase transformation between a paramagnetic high-temperature high-symmetry phase (austenite) and a ferromagnetic low-temperature low-symmetry phase (martensite). The low-temperature martensite phase consists either of both or one of the differently oriented hierarchical twinning configurations, where magnetic domain direction is alternatively out of plane and in plane (X-type) or in plane (Y-type) [2,3]. Different arrangement of these twinning configurations gives rise to various magnetic properties. In our previous works, we have reported a number of strategies for engineering these hierarchical twinning assembles in epitaxial Ni-Mn-Ga films, in most of which we succeeded in inducing, aligning, or expanding the portion of Y-type twinning configurations [3-5].

In this study, we report a simple strategy for the reverse process by converting the entire microstructure of the samples into X-type. We show that the twinning configurations of 200-nm Ni-Mn-Ga films, epitaxialy grown on MgO(001) using Cr underlayer, can be permanently converted into X-type by a single-step post-annealing treatment. We evidence that this simple twinning configuration engineering approach is applicable not only to continuous films but also to patterned micrometer structures of Ni-Mn-Ga. Finaly, advanced characterization techniques including temperature dependent scanning tunneling microscopy (STM) and low-energy electron diffraction (LEED) enable us analyzing the atomic structure and surface of the samples. The simple microstructure engineering strategy reported in this study facilitates magnetic manipulation of shape-memory Heuslers in miniaturazed functional devices.

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Anomalous Nernst effect in GdCo alloys for heat flux sensing

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A Heat Flux Sensor (HFS) enables heat flow visualization unlike a temperature sensor, and is expected to be an elemental technology in a waste heat management society. Recently, Zhou et al. proposed an HFS that utilizes the Anomalous Nernst Effect (ANE)[1]. The ANE-based HFS has the advantage of being a thin film, making it easy to manufacture devices with good reproducibility, and making it easy to make it flexible. The key parameter in evaluating materials for ANE-based HFS is the ratio of thermal electromotive force (E) induced by ANE to the heat flux density (j), expressed as E/j. According to Fourier's law and the definition of the transverse Seebeck coefficient (S_{ANE}), this ratio is given by: $E/j = S_{\mathrm{ANE}}/\kappa$, where κ is the thermal conductivity. This equation underlines the necessity for materials with a high transverse Seebeck coefficient and low thermal conductivity for effective HFS design. Additionally, materials that exhibit bipolarity in S_{ANE} are advantageous for modular HFS designs. However, there are no reports on materials with negative polarity of the sensitivity [1-4]. In this study, we have investigated ANE in amorphous GdCo alloys[5].

The sample structure is Si_3N_4(10 nm) /Gd_xCo_{100-x}(20 nm) /Si_3N_4(3 nm), which was deposited on SiO_2 glass substrates using magnetron rf and dc sputtering techniques. S_{ANE} (E/j) was measured under conditions of a perpendicular (an in-plane) magnetic field and an in-plane (a perpendicular) thermal gradient. Figure (a-b) depicts the composition dependences of S_{ANE} and E/j. Gd doping enhances S_{ANE} and its magnitude remains over 1.0 µV/m across a wide composition range, including the Magnetization Compensation Point(MCP). The polarity of S_{ANE} is changed at MCP. The dependency of E/j is reminiscent of that of S_{ANE}. Our results reveal that doping Gd into the alloy significantly enhances the sensitivity (E/j). Remarkably, the sensitivity peaks at 0.20 µm/A over a broad composition range and its maximum is 0.23 µm/A as $x = 23.7$. This value is comparable to the highest sensitivity found in Co_2MnGa[2]. Additionally, the composition dependence of S_{ANE} suggests that the high sensitivity originates from the coexistence of a relatively large S_{ANE} (over 1.0 µV/K) and low thermal conductivity. The observed bipolarity of the large sensitivity is particularly advantageous for a thermopile structure.

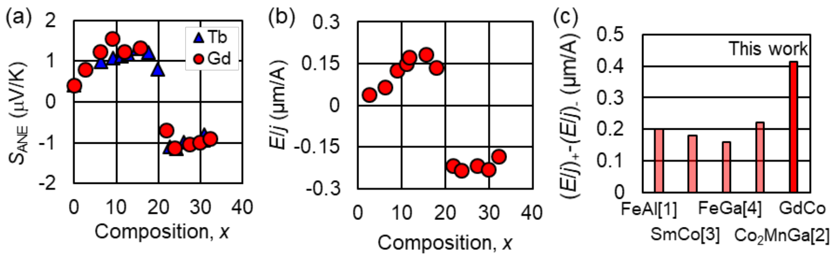

Figure 1: S_{ANE}(a) and E/j(b) as a function of composition. (c) Comparison between this study and previous studies. $(E/j)_{+(-)}$ indicates E/j in a material with $S_{\mathrm{ANE}} > 0\,(< 0)$. $(E/j)_+ - (E/j)_-$ is the sensitivity as thermopile materials for an HFS. FeAl, SmCo, FeGa, and Co_2MnGa indicate in the previous reports, respectively.

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Anomalous Nernst effect in nanoporous Co thin films

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The Anomalous Nernst effect (ANE) is the transverse thermoelectrical conversion phenomena and expected as the new energy harvesting technology. This effect typically occurs in ferromagnetic materials and defined as a generation of the electrical field in the vertical direction to both the magnetization of the sample and the applied temperature gradient. In contrast to the Seebeck effect, which is limited to generate electrical field in the parallel direction of the temperature gradient, ANE allows us to create more flexible and useful devices with better scalability. However, ANE conversion efficiency is too small to use practically, thus it is large issue to search materials which have a large ANE. Recently, we have reported the enhancement of the ANE in the granular thin films[1]. On the other hand, porous structure is well known as materials with large amounts of pores. In this study, we investigated the ANE in the porous Co thin films with different pore sizes and investigated porosity-dependence on the ANE.

We prepared porous Co thin films by vapor phase dealloying method[2]. First, we fabricated CoZn thin films on a MgO(001) substrate by co-sputtering method. Then we annealed the films by using a rapid thermal annealing system to evaporate only Zn and create porous structures. The crystallographic structures were observed by a scanning electron microscope (SEM). The Nernst voltage was measured by a physical property measurement system (PPMS) with a perpendicular magnetic field to the film plane at room temperature and transverse Seebeck coefficient was estimated to examine the ANE properties.

Figure 1 shows a SEM image of the porous Co thin films, which was annealed at 400˚C for 10 minutes. The bright and dark regions are Co matrix and pore, respectively. Averaged pore size is approximately 50 nm, and it is confirmed that nanoporous films are obtained. Figure 2 shows the transverse Seebeck coefficient (S_{xy}), which expresses the magnitude of the ANE, of porous film (same as Fig. 1) and non-porous film. As shown in th figure, S_{xy} of the porous film (0.24 μV/K) is slightly larger than that of the non-porous film (0.21 μV/K). It is also revealed that the ANE angle (θ_{ANE}) increases from 0.011 to 0.037 by the formation of nanoporous structures. The porosity-dependence of the ANE will be discussed in detail.

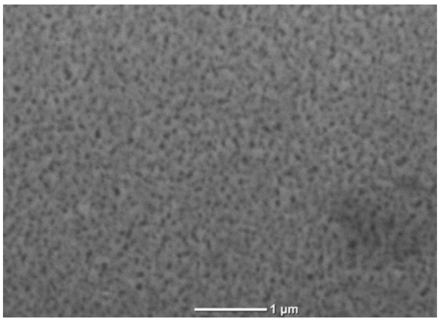

Fig. 1 SEM image of porous Co film annealed at 400˚C for 10 min.

Fig. 2 S_{xy} of porous and non-porous films.

This work was partially supported by a Grant-in-Aid for Science Research S (Grant No.21H05016).

[1] P. Sheng, T. Fujita, and M. Mizuguchi, Appl. Phys. Lett., **116**, 142403 (2020).

[2] Z. Lu, *et. al.*, Nat. Commun., **9**, 276, (2018).

Anomalous Nernst effect in nanoporous Co thin films

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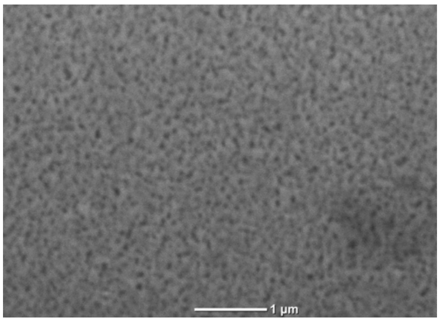

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Temperature-induced magnetic differentiation of equivalent Mn lattice sites in the epitaxial Mn_2GaC film monitored by NMR.

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Mn_2GaC films belong to the MAX phase family presenting an inherently nanolaminated structure stacked along the hexagonal c-axis, where the covalently bound Mn-C-Mn blocks are interleaved with the atomic layers of Ga. This compound is magnetically ordered below 507 K where the strongly coupled ferromagnetic Mn-C-Mn blocks are antiferromagnetically arranged across the Ga layer. At around 214 K this compound undergoes a first-order phase transition to a noncollinear spin arrangement – magnetization of the consecutive Mn-C-Mn blocks realigns from the original 180˚ to reach a twist angle of 167˚, giving rise to a long–range helical magnetic structure extending along the c-axis [1]. In addition, our previous NMR study performed at 4.2 K on a 100 nm thick film grown on the MgO substrate revealed the presence of magnetically non-equivalent Mn positions among the equivalent crystallographic sites - up to four NMR lines could be resolved in the NMR spectrum, each showing the same helical arrangement of the magnetic moments [1]. To follow this transition and understand the local magnetic properties in the Mn lattice we have now performed an extended study on the same film, recording the ^{55}Mn NMR spectra at several different temperatures ranging from 240 K down to 4.2 K. The experiment shows that the complex NMR spectrum observed at 4.2 K reflects a site-dependent strain, adding a new local field component in particular lattice sites via a magnetoelastic reaction.

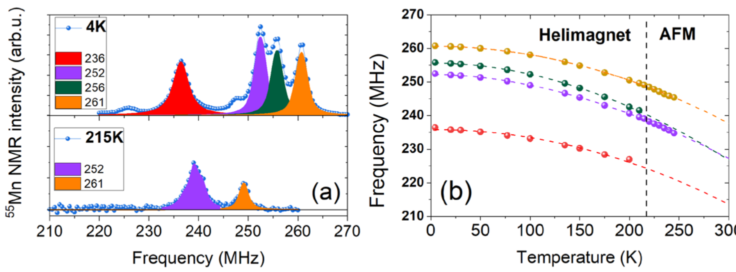

Figure 1: a) ^{55}Mn NMR spectra recorded from the Mn_2GaC film at and below the phase transition b) Temperature dependence of different spectrum components.

This work has been supported in part by a grant from the National Science Center, Poland (UMO-2019/35/B/ST3/03676).

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Spin–orbit torque on nuclear spins via hyperfine interactions

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Spin-transfer and spin–orbit torques allow controlling magnetic degrees of freedom in various materials and devices. However, while the transfer of angular momenta between electrons has been widely studied, the contribution of nuclear spins has yet to be explored further. This article demonstrates that the hyperfine coupling, which consists of Fermi contact and dipolar interactions, can mediate the application of spin–orbit torques acting on nuclear spins.

Our starting point is a sizable nuclear spin in a metal with electronic spin accumulation. By using linear response theory, we show that the magnetic hyperfine interaction induces a magnetization, *i.e.* spin density, on conduction electrons around the nuclear spin. When the metal has spin accumulation, the electronic magnetization is not parallel to the nuclear spin and exerts a nuclear spin orbit torque on the nucleus. The reactions to the equilibrium and nonequilibrium components of the spin density is a torque on the nucleus with field-like and damping-like components, respectively.

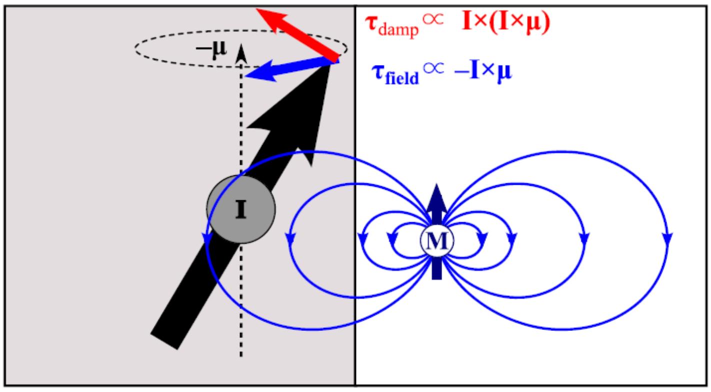

Figure 1. Hyperfine interaction between magnetizations of nucleus and conduction electron generates a torque on nuclear spin. Here, τ_{field} is field-like torque and τ_{damp} is damping torque.

In particular, the nuclear spin orbit torques is large for a bilayer of ferromagnet with high spin nucleus and nonmagnetic metal with high magnetic permeability, such as Fe, which has a stable isotope ^{57}Fe. In NMR quantum computing, nuclear spin is a candidate for qubit. Since qubit has the potential to the miniaturization of memory, the application of nuclear spin by means of nuclear spin-orbit torque could lead to further miniaturization of spintronics devices. Therefore, this nuclear spin–orbit torque is a step toward stabilizing and controlling nuclear magnetic momenta, in magnitude and direction, and realizing nuclear spintronics.

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Spin-wave modes and real-space topology in the quadruple-Q magnetic hedgehog lattices

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Magnetic hedgehogs and antihedgehogs are sources and sinks of emergent magnetic fields in three-dimensional magnets, and thus behave as virtual magnetic monopoles and antimonopoles, respectively. Magnetic hedgehog lattices, in which vortex strings connecting hedgehog-antihedgehog pairs called Dirac strings align in a spatially periodic manner, have been experimentally discovered recently in the B20 compounds $MnSi_{1-x}Ge_x$ [1] and a perovskite iron oxide $SrFeO_3$ [2]. As is the case with the 2D skyrmion crystals with various spin-wave modes such as rotational, breathing, and polygonal modes [3], it is expected that the 3D magnetic hedgehog lattices also have a variety of spin-wave modes associated with the magnetic topology which characterize the real-space spin textures. Explorations of such spin-wave modes in topological spin textures are very important because they are closely related with dynamical phenomena in microwave/light frequency domains and manipulations of topological magnetisms with microwaves or light.

We theoretically study the spin-wave modes in the quadruple-Q magnetic hedgehog lattices by constructing a Kondo-lattice model based on the microscopic insights and by analysing it using real-time simulations combined with the Chebyshev polynomial expansion techniques [4]. We find three spin-wave modes, named L1, L2, and L3 modes, in the sub-terahertz regime which correspond to the longitudinal translational oscillations of Dirac strings. It is clarified that their spatial profiles sensitively depend on the real-space topology of the hedgehog-antihedgehog spin textures. Specifically, the L2 (L3) mode is localized around the hedgehogs and antihedgehogs that belong to the Strings B (A) with vorticity of -1 (+1). These modes disappear upon the topological phase transitions associated with pair annihilations of the hedgehogs and antihedgehogs. This finding enables us to detect topological phase transitions associated with the pair annihilations of monopole-antimonopole pairs. The knowledge obtained in the present work is expected to open a new research field for novel dynamical phenomena and microwave/optical device functions of 3D topological magnetism.

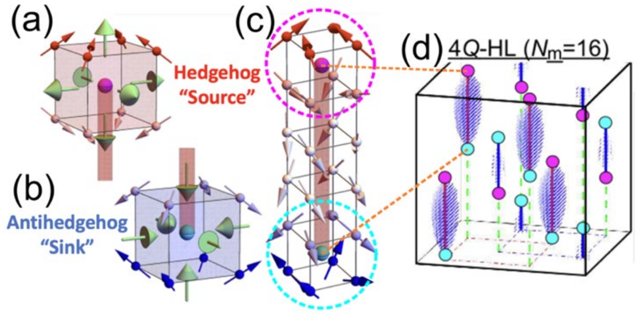

Figure: (a)-(c) Schematics of (a) a magnetic hedgehog, (b) an antihedgehog, and (c) the Dirac string A. (d) Spin arrangement of the quadruple-Q magnetic hedgehog lattice. Red (blue) lines show the strings A (B) with a vorticity of +1 (-1).

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Towards a skyrmion-based magnetic field sensor

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Spintronic sensors based on magnetoresistive effects have been widely studied over the past years for various applications, due to their small dimensions, reduced cost and high magnetic field sensitivity [1]. Magnetic skyrmions are localized chiral spin textures, promising for next-generation spintronic devices. In addition to the initially proposed applications such as skyrmion storage and logic devices, an emerging outcome of skyrmion multilayer studies is their potential use in sensing applications [2].

High sensitivity to external magnetic fields combined with an almost linear response in a very narrow magnetic field range and a small saturation field, mark ideal properties for the fabrication of a magnetic field sensor highly sensitive to very small out-of-plane magnetic fields. Here, we study a heavy-metal/ferromagnet/metal oxide magnetic trilayer, as shown in Figure 1**a**, with perpendicular magnetic anisotropy (PMA). The PMA depends on the ferromagnetic FeCoB layer's thickness, sandwiched between a Ta and a TaO_x layer. Our optimized material parameters, in particular FeCoB thickness and the top Ta layer (subsequently oxidized), allows a control of the magnetic and interfacial properties of the FeCoB layer. The complex balance between anisotropy, exchange, Dzyaloshinskii-Moriya, dipolar and Zeeman energy defines the magnetic domain pattern in the PMA region [3]. Approaching the transition region of PMA to paramagnetic regime, low domain wall energy allows thermal demagnetization and nucleation of skyrmions by the application of extremely small external magnetic fields (μT range). In Figure 1**c-d**, the magneto-optical Kerr effect (MOKE) microscope images of skyrmions and chiral domain walls illustrate the evolution of the magnetic domain pattern under magnetic field. We convert the magnetic response to an electrical signal, using the extraordinary Hall effect (see Figure 1**b)**. We observe extremely low saturation fields in the range of 200 μT and a quasi-linear response. To evaluate the applicative potential of this skyrmion material for developing perpendicular magnetic field sensor, we will perform noise characterization and evaluate the detectivity.

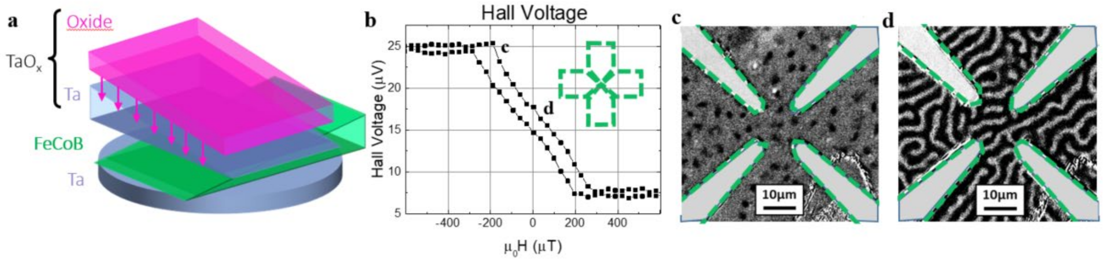

Figure 1: (a) Double wedge trilayer used for the study. (b) Hall voltage measurement as a function of the external magnetic field. (c, d) MOKE images of skyrmions and chiral domains at the center of the Hall cross.

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Microstate, geometry and their footprints in dynamic spin wave properties in artificial spin ice

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Using the GPU accelerated software mumax^3 and Fourier analysis, we perform micromagnetic simulations with regard to the spin dynamics at remanence in a periodic square artificial spin ice (ASI). We consider four different microstates characterized by a specific number of magnetic charges at the central vertex of the primitive cell. Each ASI element - regarded as a macrospin - consists of permalloy elliptical dot with fixed long axis and thickness (256 and 5 nm, respectively), variable width and interdot separation, saturation magnetization 800 kA/m and exchange stiffness 13 pJ/m [1, 2]. Equilibrium ground states are computed for each microstate and are excited by applying a uniform sinc pulse perpendicular to the plane. We perform Fourier analysis to obtain frequency spectra and space phase profiles. The results establish a correlation between ASI macrospin orientation at vertices and key dynamic properties: first, we notice a phase-shift in the fundamental and edge mode profiles as a function of the macrospin separation and width as well as of the magnetic charges at vertex. We also register a frequency gap between the edge and fundamental modes that increases for increasing effective charge at a vertex: this is due to the presence of more intense demagnetizing fields. Furthermore, the role of the macrospin density and width in the array is investigated; we also focus on the absolute size of a macrospin, responsible for the richness of modes and peaks in the spectrum [3]. These findings demonstrate the footprints left in the dynamics by the specific orientation of the macrospin magnetization at the ASI vertices. Our results suggest specific experiments for validation (e.g. how dynamic measurements can be employed to investigate the statics of the system, with special regard to ferromagnetic resonance - FMR - and Brillouin light scattering - BLS - techniques). Finally, applications in interferometric magnonic logic devices and spin waves computing are proposed: for example, the aforementioned spin wave phase-shift, which can be properly regulated by triggering specific macrospin reversals.

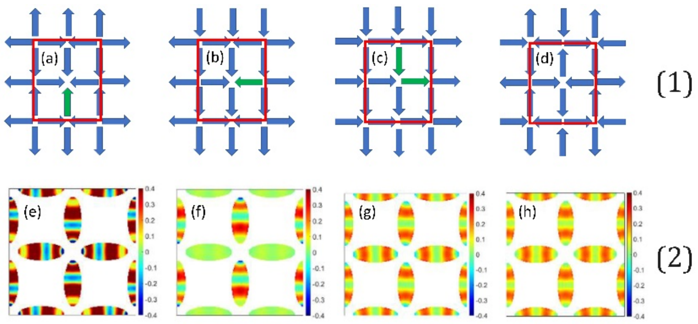

Figure 1: Panel (1). The four microstates in the square ASI: (a) 4N; (b) 3N1S; (c) 2N2S; (d) Vortex, i.e. a closure distribution. The red square frame encloses the primitive cell while the green arrows indicate the macrospins at vertex which are switched in order to move from one microstate to the following one. Panel (2). Fundamental mode profile for the different ASI microstates: (e) 4N, (f) 3N1S, (g) 2N2S, (h) Vortex.

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Coupling of the triple-Q state to the atomic lattice

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The triple-Q (3Q) state – a three-dimensional spin structure on a two-dimensional lattice predicted about 20 years ago [1] – has recently been observed in a Mn monolayer on Re(0001) using spin-polarized scanning tunneling microscopy (SP-STM) [2]. The 3Q state is a superposition of three symmetry equivalent spin spirals with the same period and can be stabilized by higher-order exchange interactions (HOI) such as the biquadratic or four-spin interactions [1,2]. The ideal 3Q state with tetrahedron angles between nearest-neighbor spins does not exhibit a net spin moment. However, theoretical investigations have shown a significant topological orbital magnetization and a spontaneous topological Hall effect, without the necessity of spin-orbit coupling [3,4]. From the SP-STM experiments on Mn/Re(0001) it was also concluded that the 3Q state couples to the atomic lattice in a specific orientation [2]. However, the coupling mechanism could not be revealed.

Here, we demonstrate that the 3Q state is coupled to a hexagonal atomic lattice in a highly symmetric orientation via the anisotropic symmetric exchange interaction, whereas other spin-orbit coupling terms cancel due to symmetry [5]. Density functional theory calculations show that the ideal 3Q state is realized in Pd/Mn and Rh/Mn bilayers on Re(0001), while a significantly distorted 3Q state occurs in Mn/Re(0001) [6] due to the frustration of higher-order exchange interactions. This leads to two distinctively different orientations of the 3Q state with respect to the atomic lattice [5]. SP-STM experiments are in agreement with the predicted orientations of the ideal 3Q state and the distorted 3Q state (Fig. 1).

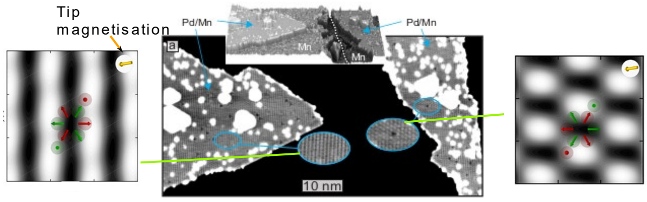

Figure 1: SP-STM image of Pd/Mn/Re(0001). Two islands can be seen in the experimental image (center). The blue ellipses show a zoom of regions on the islands. SP-STM images calculated for the 3Q state based on DFT are shown for comparison to the left and right. The yellow arrows indicate the tip magnetization used for these calculations.

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Detection of ferroic Berry curvature dipole in a topological crystalline insulator, PbSnTe

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Berry curvature is the key physical trait in topological quantum materials (TQMs). Indeed, a wide variety of TQMs have been discovered and rise of the era of TQM was achieved. Among various topological features appearing in TQMs, the Berry curvature dipole (BCD) is a significant and intriguing phenomenon that requests inversion symmetry breaking of the topological systems. Meanwhile, despite the attractiveness of the BCD, the material stages for the BCD are still limited and the temperature range for it is far below room temperature (RT). Furthermore, nonvolatile, i.e., ferroic BCDs have not yet discovered in spite of its prediction in theory [1].

In this presentation, we introduce the successful detection of the ferroic BCD at RT in a topological crystalline insulator, PbSnTe [2]. The nonlinear Hall effect, where no external magnetic field is applied, is a good probe for the BCD. Unlike topologically trivial PbTe, PbSnTe exhibits salient nonlinear Hall effect (see. Fig. 1). The magnitude of the BCD largely exceeds that of for example transition metal dichalcogenides. More detailed physics will be discussed in the presentation. Our findings can open an avenue to for further progress of TQMs and for engineering novel topological devices.

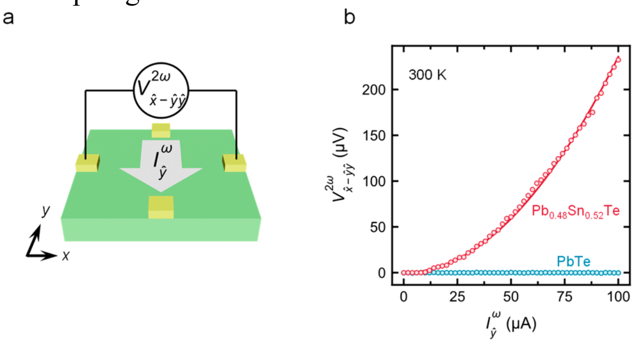

Fig. 1 (a) Experimental set-up to detect the nonlinear Hall voltage. (b) The nonlinear Hall voltages from PbSnTe (topological crystalline insulator) and PbTe (topological trivial material) at 300 K.

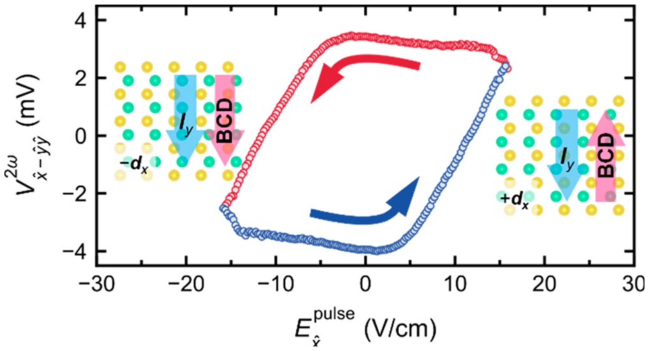

Fig. 2 Ferroic behavior of the nonlinear Hall voltages as manifestation of the ferroic BCD.

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Observation of the sliding phason mode of the incommensurate magnetic texture in Fe/Ir(111)

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The nanoscopic magnetic texture forming in a monolayer of iron on the (111) surface of iridium, Fe/Ir(111), is spatially modulated and uniaxially incommensurate with respect to the crystallographic periodicities [1]. As a consequence, a low-energy magnetic excitation is expected that corresponds to the sliding of the texture along the incommensurate direction, i.e., a phason mode, which we explicitly confirm with atomistic spin simulations. Using scanning tunnelling microscopy (STM), we succeed to observe this phason mode experimentally. It can be excited by the STM tip, which leads to a random telegraph noise in the tunnelling current that we attribute to the presence of two minima in the phason potential due to the presence of disorder in our sample [2]. This provides the prospect of a floating phase in cleaner samples and, potentially, a commensurate-incommensurate transition as a function of external control parameters.

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Six-fold angular-dependent magnetoresistance in four-fold Fe (001) films

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Anisotropic magnetoresistance (AMR) is a fundamental spin-dependent transport property, arising from spin-orbit coupling and anisotropic s-d scattering. Traditionally, in polycrystalline materials [1], the relationship between resistivity (ρ_{xx}) and the magnetization angle (θ_M^{xy}) is expressed as $\rho_{xx}(\theta_M^{xy}) = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\theta_M^{xy}$. In single crystals with cubic structures [2], owing to symmetry considerations, an additional term $\rho_4 \cos 4\theta_M^{xy}$ is introduced to the AMR expression. Notably, higher-order angular dependencies are commonly overlooked in cubic systems, presenting a valuable avenue for further investigation.

In this contribution, we grew single crystal Fe films on $MgAl_2O_4$ (001) substrate by magnetron sputtering, with thickness ranging from 3 nm to 100 nm. Subsequently, the films were fabricated into Hall bar devices, where the current flowed along Fe [100] and [110]. Measurements of ρ_{xx} and ρ_{xy} were conducted with magnetic field rotating in the (001) plane. Notably, ρ_{xx} of 6 nm j//[100] device exhibited a strong six-fold angular dependence at 5 K, despite the Fe (001) plane being four-fold. Further analysis by Fourier transformation revealed an even higher eight-fold and ten-fold angular dependence. The planar Hall effect (PHE), represented by $\rho_{xy}(\theta_M^{xy})$, shares a common physical origin with AMR. Intriguingly, the AMR in the j//[100] device and the PHE in the j//[110] devices exhibited similar angular dependencies, aligning with the prediction of the phenomenological model based on crystal symmetry [3]. We propose that the 6-fold term observed may be a result of the multiplication of polycrystalline $\cos 2\theta_M^{xy}$ contribution and the BCC crystal symmetry-induced $\cos 4\theta_M^{xy}$ angular-dependent density of states.

This discovery significantly advances our comprehension of the angle-dependent characteristics of AMR in single-crystal ferromagnetic films, providing novel insights for investigating the underlying mechanisms of AMR.

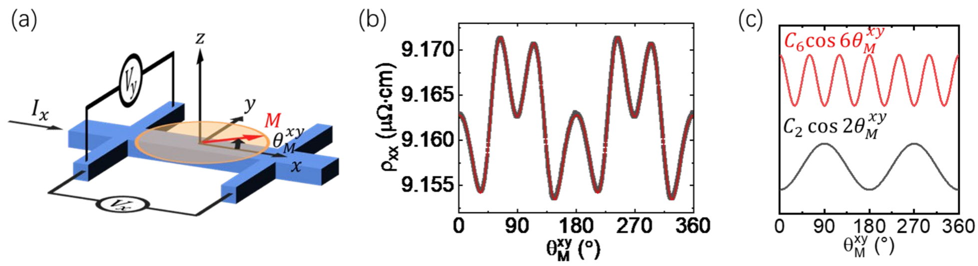

Figure 1: (a) The Hall bar device for AMR and PHE measurement. (b) Angular dependence of AMR in 6 nm j//[100] device at 5 K. (c) Decomposition of the AMR signal.

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Experimental and Numerical Demonstration of Spin-Wave Self-Imaging in YIG film

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Expanding self-imaging from optics to magnonics, we experimentally and numerically demonstrate spin-wave (SW) self-imaging in an in-plane magnetized yttrium iron garnet (YIG) film. Using Brillouin Light Scattering (BLS), we detect interference patterns as a spin plane wave passes through a diffraction grating [1]. By varying source dynamic magnetic field frequencies from antenna, we analyze the influence of anisotropic dispersion and caustic effects [3]. Our findings show that caustics dominate interference at low frequencies, while high diffraction orders create self-imaging and Talbot-like patterns [2] at far distances. This systematic approach deepens our understanding of SW interference in anisotropic media.

The samples comprised 4.5 µm thick monocrystalline YIG films grown on transparent gadolinium gallium garnet substrates. We etched a one-dimensional array of antidots onto the film surfaces to create a diffraction grating: a 10-element square antidot array (50 × 50 µm, Fig. 1a) with

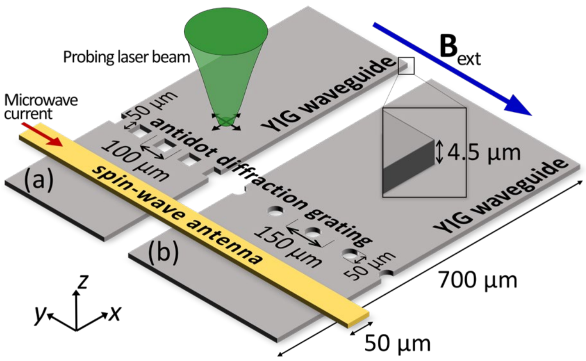

Figure 1: Schematic representation of the YIG-sample and BLS measurement configuration used in the research, with the major dimensions marked. Image (a) shows the system with a diffraction grating made of square-shaped antidots, while (b) shows one made of circular antidots.

a d = 100 µm period, and a 5-element circular antidot array (diameter 50 µm, Fig. 1b) with a d = 150 µm period. Using external magnetic fields ($\mathbf{B}_{ext}$) of 36 mT and 98 mT for square and circular antidot samples, respectively, we magnetized the samples along the y-axis. Magnetostatic SWs were excited with a 50 µm wide microstrip antenna and a continuous-mode microwave generator. To visualize SW interaction with the antidot lines, we employed a BLS spectrometer with 30 µm spatial resolution in the reflection setup. We scanned a 532 nm laser beam over the antidot line and the interference area behind the grating with a 20 µm step, recording BLS intensity at each point.

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Electromagnet end station for x-ray magnetic circular dichroism

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We report on state of an electromagnet end station for x-ray magnetic circular dichroism (XMCD). This end station has been installed on the absorption branch of the Beamline for Advanced Dichroism Experiments (BLADE). At the Diamond Light Source (DLS), BLADE is a soft x-ray beamline optimized for studies of magnetic materials using x-ray magnetic circular dichroism.

The absorption branch has been originally equipped with the superconducting high field magnet that can provide the field up to 14T and cool samples down to 3K. The operation of the high field magnet is however time demanding and it suffers from the remanent field of about 20 mT so when small magnetic field is applied, the magnetisation cannot be determined accurately. Hence, the need for a complementary end station which would provide accurate small field and high throughput.

The electromagnet end station is built around commercial coil from GMW Associates providing the field up to 1.9T. The sample can be cooled with a flow of liquid helium using vertically mounted cryostat Janis ST-400. The base temperature is about 15K. Samples can be cleaved in-situ or annealed to the temperature of 500K.

Figure 1: Image of the electromagnet end-station connected at the end of the absorption branch of I10.

The electromagnet system has been successfully tested and routinely used since 2021. An example of experimental result will be presented [1]. It is open to users via standard DLS proposal route.

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True resistivity in magnetite epitaxial ultra-thin films

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Magnetite is an exceptional compound due to the combination of magnetic and transport properties that is rare for oxides. Its quasi-metallic conductivity at elevated temperatures abruptly drops by two orders of magnitude across the Verwey transition(VT) at around 125K. In parallel, the high Curie temperature makes magnetite thin films interesting for spintronics, but their magnetic and electrical properties undergo significant modifications with decreasing thickness. It has been reported that antiphase boundaries(APB's), which strongly influence the magnetic properties, are also responsible for a large reduction in electrical conductivity [1]. In the present contribution we postulate and prove additional origin of this effect.

Our research was motivated by comparing *in situ* and *ex situ* conversion electron Mössbauer spectroscopy (CEMS) measurements on ultrathin magnetite films grown under UHV conditions. We found that these films oxidize toward maghemite when exposed to the atmosphere. For this reason, to reveal the true character of the thickness dependence of the resistivity in magnetite, the electrical measurements should be performed *in situ* under UHV. This was possible by using special sample holders with electrical contacts to molybdenum pads predeposited on MgO(001) (Fig.1a).

Epitaxial magnetite $Fe_3O_4(001)$ films with different thicknesses were grown on MgO(001) by reactive deposition of Fe under the O_2 partial pressure of $5*10^{-6}$ mbar on the substrates kept at 530 K. We measured a thickness and temperature dependence for a series of the $Fe_3O_4(001)$ films in the thickness range from 2 nm to 50 nm. The thickness dependence (an example of an in situ measurement during growth is shown in Fig. 1b) is discussed based

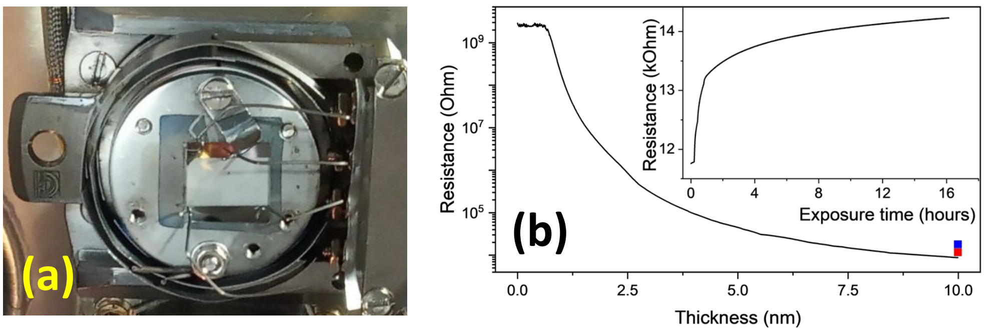

Figure 1. (a) Sample holder for in situ electrical measurements. (b) In situ resistance during growth of a $Fe_3O_4(001)$ film on MgO(001) with a final thickness of 10 nm. The points and inset show a resistance increase after O_2 adsorption and exposure to ambient atmosphere.

on classical models and contribution of APB's is estimated. For the available measurement temperatures (T_{min}= 100 K) we found VT for films as thin as 5 nm. The effect of oxygen adsorption and prolonged storage in the ambient atmosphere is also discussed.

This research was funded by National Science Centre, Poland (NCN), grant number 2020/39/B/ST5/01838.

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Tuning the angular dependence of the switching field of thin film nanomagnets

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Bistable single-domain nanomagnets have a wide range of applications, for example as building blocks of magnetic metamaterials. We can tailor the magnetic properties of such metamaterials by controlling the way the nanomagnets interact through their stray fields. To do this, we must have a thorough understanding of how magnetic fields affect the nanomagnets when applied at different angles. For elliptical nanomagnets, the Stoner-Wohlfarth model captures the angular dependence of the switching field well[1]. However, other shapes have significantly different switching characteristics. Although systematic studies show that angular switching characteristics in both thin film nanomagnets and magnetic nanoparticles change dramatically when the shape and size of the nanomagnets are varied[2,3], most studies investigate switching purely in simulation. Using state-of the art electron beam lithography, we fabricate several arrays of thin film nanomagnets, as shown in figure 1a. The fabricated arrays consist of rectangular, elliptical or stadium-shaped nanomagnets, of varying width, length and thickness. We experimentally quantify the angular dependence of the nanomagnet coercivity using MOKE-microscopy. By comparing the experimental results to micromagnetic simulations, we try to develop a framework for predicting the switching characteristics of thin film nanomagnets based on their shape and size, which could be used in the design of new magnetic metamaterials with exotic magnetic properties.

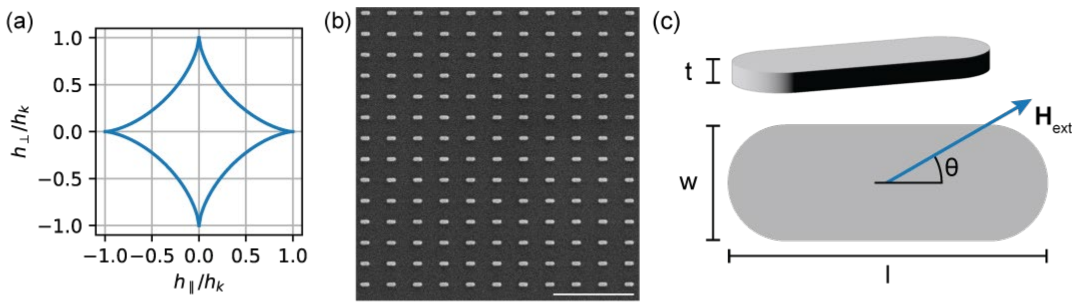

Figure 1: (a) SEM image of nanomagnet array, comprised of 220x80 nm stadium-shaped nanomagnets. (Scale bar: 2 um) (b) The switching field of the nanomagnet depends on the width, length, thickness of the magnet and the angle of the applied field.

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CoPd-based perpendicular synthetic antiferromagnetic layers with strong exchange coupling oscillation

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National Institute for Materials Science, Japan

Magnetic tunnel junctions (MTJs) are a fundamental component used for the magnetoresistive random access memory (MRAM) and many other spintronics devices. Data of MRAM cells is stored by changing the magnetization direction of the ferromagnetic layer (free layer) whereas the other ferromagnetic layer keep its magnetization fixed (reference layer). A synthetic antiferromagnetic (SAF) layer is often used to stabilize the magnetization state for nano-scale perpendicularly magnetized MTJs (p-MTJs). CoPt-based SAF layers are commonly used due to its large perpendicular magnetic anisotropy and thermal stability [1]. However, the use of a heavy Pt element can be difficult to handle using Ar-based sputtering processes due to high energy recoil which can damage the film surface [2]. Lighter Pd would be a suitable option for a perpendicular SAF system [3]. CoPd alloys are known to have a much lower damping constant compared to CoPt [4], which is promising for application as a free layer in spin transfer torque (STT)-MRAMs.

We developed CoPd-based SAF layers as a pinning layer for a p-MTJ structure. Stacks with a structure of (Si/SiO_2) substate/Ta/Ru/Pd/$[Co/Pd]_5$/Co/Ru (t_{Ru})/$[Co/Pd]_2$/Co/W were deposited using ultra-high vacuum DC/RF magnetron sputtering (See Fig. 1 a)). The stacks were annealed at 350–400°C for 30 min. Magnetic hysteresis was measured by polar magneto-optic Kerr effect system. As shown in Fig. 1 b), the exchange coupling field reached up to 10 and 6 kOe for its first (t_{Ru} ~ 2.5 Å) and second antiferromagnetic peak (t_{Ru} ~ 8 Å). These coupling fields are larger compared to the previous report [5]. Moreover, the exchange coupling can be maintained even after annealing at 400°C, which is required for the CMOS back-end-of-line process. These results indicates that CoPd-based SAF layer has large potential for STT-MRAMs. This work was partly supported by Samsung Japan Corporation and by JSPS KAKENHI via Grant Nos. 21H01750 and 22H04966.

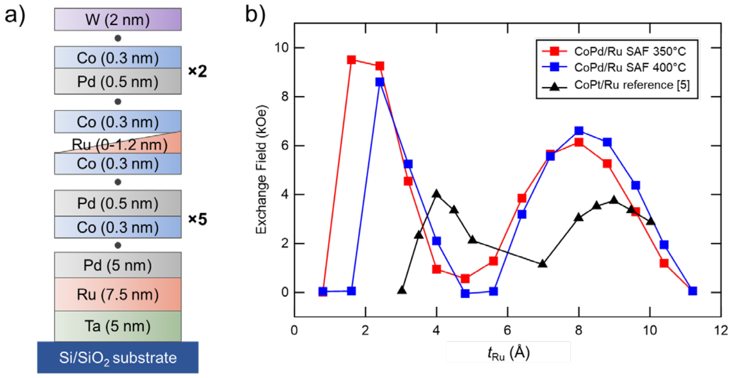

Figure 1. a) Layered stacking of CoPd-SAF layer. b) Ru spacer thickness (t_{Ru}) dependence of perpendicular exchange coupling field.

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Geometric-magnetic chirality coupling in double-helix nanostructures

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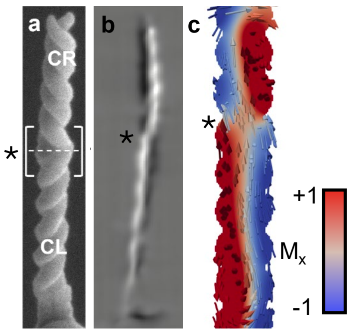
Artificial double-helix ferromagnetic nanostructures combine a chiral geometry and competing exchange/dipolar inter-strand coupling [1]. Additionally, the geometrical control of magnetic chirality enables the connection of spin states with opposite magnetic chirality through chirality interfaces. All this results in a rich and tuneable magnetic platform to study chiral effects in three dimensions, including the imprinting of chiral 3D spin textures [1], and of stray fields with topological features [2].

In this contribution, we will present XMCD ptychography imaging experiments in these systems under external magnetic fields [3]. First, we will show how we can fabricate and finely tune the geometry and magnetic material of these nanostructures thanks to "f3ast", our open-access 3D nano-print software for focused electron beam induced deposition [4]. Secondly, we will show how the application of fields during a major hysteresis loop leads to the formation of two interfaced helical-vortex states at remanence, which demonstrate the coupling between geometrical and magnetic chirality. Finally, we will show how under particular field sequences, it is possible to magnetically reconfigure the system and break the geometrical-magnetic coupling. Under these conditions, we observe the formation of a single helical-vortex tube at remanence extending along the entire system, and we can follow its evolution under applied magnetic fields. We will discuss the different topology of the two distinct states identified, as well as possible applications of 3D magnetic interconnectors with reconfigurable topological spin states [5].



(a) SEM image of a double helix system with two domains of opposite geometric chirality (CL, CR). (b,c) XMCD magnetic image and micromagnetic simulation corresponding to two helical-vortex states connected by a chirality interface (*)

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Effect of Si substitution on the local magnetic properties of the $Mn_5(Ge_{1-x}Si_x)_3$ /Ge(111) epitaxial films

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Antiferromagnetic Mn_5Si_3 compound shows many interesting phenomena such as the topological Hall effect, inverse magnetocaloric effect or recently reported altermagnetism. A collinear spin arrangement (AF2) observed below the Neél point (T_N=99K) becomes frustrated at 65K, resulting in a non-collinear magnetic structure (AF1) the details of which are still a subject of debate. To follow the formation of the AF1 magnetic structure we performed a systematic NMR study on a series of $Mn_5(Ge_{1-x}Si_x)_3$ ($0 \le x \le 0.55$) epitaxial films starting from the isostructural ferromagnetic Mn_5Ge_3 compound (x=0), the NMR features of which have been well-understood [1]. The unit cell contains two formula units, with the manganese atoms in two Wyckoff crystallographic positions: 4*(d)* (Mn_I) and 6*(g)* (Mn_{II}). The pristine Mn_5Ge_3 composition features two NMR lines centered around 207.5 MHz (Mn_I site) and 428 MHz (Mn_{II} site) [1]. A thorough analysis of the NMR experiments shows that the substitution of Ge with Si affects primarily the manganese in the 6*(g)* lattice sites, located in the same atomic plane as Ge/Si. A new population of the 6*(g)* manganese sites: Mn_{IInew} , distinguished by a lower magnetic moment has been identified, evidencing the modified exchange interactions due to a lattice distortion introduced by Si. Coexistence of the Mn_{II} and Mn_{IInew} environments in the mixed concentration region indicates that a transition from the FM order for x=0 towards the AF1 structure represents a first-order phase transition. The 4*(d)* environments are not significantly altered by Si substitution in the studied concentration range. Interestingly, a significant anisotropy of the orbital moment, characteristic for the pristine Mn_5Ge_3, was found to be unaltered in all manganese sites for all studied concentrations, in contrast to a sharp decrease of the Mn_{II} magnetic moment.

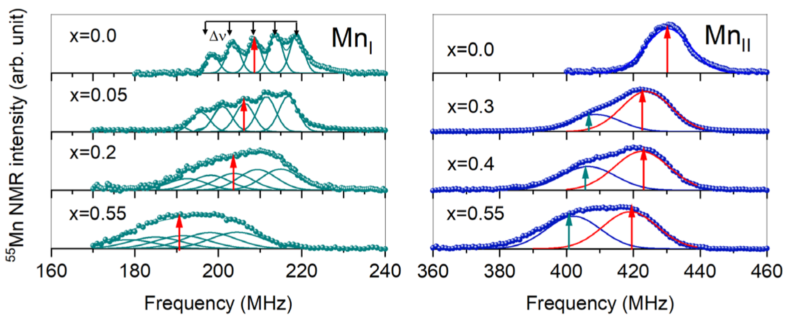

Figure 1: ^{55}Mn NMR spectra recorded from $Mn_5(Ge_{1-x}Si_x)_3$ epitaxial films. Left: quadrupolar quintuplet from the 4*(d)* site. Right: pristine and new 6*(g)* environments

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Correlations of chemical and magnetic properties in cobalt/magnetite and cobalt/hematite epitaxial heterostructures

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The aim of this research was to study metal-oxide interactions for model systems with spintronic functionality, i.e. for ultrathin cobalt adsorbates on iron oxides substrates: ferrimagnetic magnetite - Fe_3O_4(111) and antiferromagnetic hematite - α-Fe_2O_3(0001) with the special emphasis to magnetic, electronic and chemical properties transferred through the interface.

Co/Fe-oxide bilayers were deposited onto monocrystalline Pt(111) substrate as a model system as well as onto thin epitaxial (111)-oriented Pt barrier layer evaporated on MgO(111). Preparation of samples as well as their structural characterization were performed in the ultra-high vacuum (UHV) systems. Metal and oxide films were deposited by means of molecular beam epitaxy (MBE). Most of the cobalt films were grown in a form of "wedges", with a Co thickness ranging from 0.2 – 3 nm. Scanning tunneling microscopy (STM) measurements showed that self-organizing periodic lattices of cobalt nanoparticles (sized 2 - 8 nm) were obtained on the magnetite as well as on the hematite surface. The nanoparticles homogenously filled the surfaces, and their self-organization reproduced the hexagonal arrangement of *biphase* surface superstructures that are characteristic for Fe_3O_4(111) and α-Fe_2O_3(0001) [1].

Mutual interplay between the ferrimagnetic magnetite or antiferromagnetic hematite and cobalt was analyzed by means of techniques with chemical and magnetic surface sensitivity such as conversion electron Mössbauer spectroscopy (CEMS), X-ray photoemission electron microscopy (X-PEEM), X-ray absorption spectroscopy (XAS), magnetooptic Kerr effect (MOKE) and magnetic force microscopy (MFM). PEEM/XAS measurements were performed at the SOLARIS National Synchrotron Radiation Centre with the use of right and left circularly polarized X-ray radiation for the energy covering the L2,3 edges for Fe and Co [2]. The synchrotron XAS measurements showed that in the interfacial layer of Co/magnetite and Co/hematite, complementing processes of Co oxidation to CoO and iron oxides reduction take place [3]. Element sensitive PEEM-XMCD measurements showed that both for Co/Fe_3O_4 and Co/α-Fe_2O_3 magnetic domains in cobalt and in oxide are replicated due to direct exchange interactions at the metal-oxide interfaces. The observation of the XMCD contrast at the Fe L-edge in the nominally antiferromagnetic hematite film indicates the occurrence of uncompensated magnetic moments in the interface layer due to the interaction with cobalt.

This research was funded by National Science Centre, Poland (NCN), grant number 2020/39/B/ST5/01838.

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Co and Co/Cu dual-segment nanowires

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Co, Cu and Co/Cu dual-segment nanowires have been successfully synthesized through direct electrochemical deposition in anodic aluminum oxide membranes. The length of the nanowires is several microns and diameters are between 80-200 nm. The Co and Cu show hexagonal close packed crystal structure and face centered cubic crystal structures, respectively, regardless of single or multi-segmented forms. Magnetic force microscopy analysis with a magnetized probe in two opposite fields illustrates the quasi-periodic magnetization modulation along the pure Co wires and the Co segment in Co/Cu dual-segment nanowires, which suggests that interfacing a Cu segment to a Co nanowire maintain the magnetic property of Co. A pair of Co/Cu dual-segment nanowires partially in contact show interactions between the Co segments measured with a magnetic force microscope, as shown in Figure 1. The results can enhance the understanding of ferromagnetic materials interactions in a nanometer scale for the application in magnetic random-access memory.

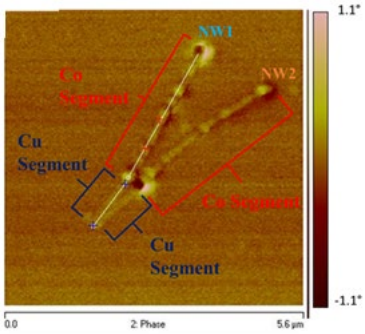

Figure 1: MFM contour image of two Co/Cu dual-segment nanowires NW1 and NW2 in contact at the Cu end.

Electrical and magnetic properties of Fe_3O_4 thin films deposited via 1st harmonic Nd:YAG laser

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The magnetite Fe_3O_4, a cubic spinel ferrimagnetic compound, has garnered significant attention due to its distinctive electrical and magnetic properties, rendering it as a promising candidate for spin electronic devices like spin valves or spin tunnel junctions. Despite its potential, realizing these unique properties in thin films for diverse device applications has proven challenging. This difficulty arises from the unpredictable formation of growth defects, particularly antiphase boundaries (APBs). Numerous investigations have indicated that the presence of APBs in Fe_3O_4 thin films leads to significant deviations in their transport and magnetic properties compared to the single crystal bulk. These deviations include a low Verwey transition, a broad transition, increased resistivity with decreasing film thickness, and superparamagnetic behavior in ultrathin films [1]. Conventional methods for depositing Fe_3O_4 films rely on pulsed laser deposition using a KrF excimer laser.

In this work, to uncover novel pathways for depositing Fe_3O_4 films and opening up new avenues for research and technological advancements, we investigated the potential of a 1st harmonic Nd:YAG laser (λ = 1064 nm) as an alternative approach. Fe_3O_4 with thicknesses ranging from 10 to 100 nm were deposited utilizing pulsed laser deposition with a 1st harmonic Nd:YAG laser (λ = 1064 nm) [2] on two distinct substrates, namely the cubic MgO (001) and the spinel $MgAl_2O_4$ (001). If the growth of Fe_3O_4 on MgO is expected to experience a smaller strain (i.e. lattice mismatch is + 0.44 %), $MgAl_2O_4$ shares with Fe_3O_4 the same crystal space group, though being affected by a larger strain (i.e. lattice mismatch is about - 3.78%). The epitaxial relationship of the films on both substrates was validated through high-resolution X-ray diffraction (XRD) which confirmed that all of the Fe_3O_4 films grow [001]-oriented. Long-range crystalline order was affirmed by Low Energy Electron Diffraction (LEED), while X-ray reflectivity (XRR) and Scanning Tunnelling Microscopy (STM) indicated a surface roughness below 1-unit cell. Temperature-dependent electrical transport properties always exhibited polaronic-like insulating behaviour while room-temperature Magnetic Optic Kerr Effect (MOKE) measurements revealed lower coercive fields in films grown on MgO compared to those grown on the spinel $MgAl_2O_4$ substrate. On the contrary, lower saturation field has been measured in Fe_3O_4 films grown on spinel $MgAl_2O_4$ substrates therefore proving that structural features (e.g. strain state, domain size) play a crucial role in determining the magnetic behaviour of magnetite.

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STM/STS study of ultrathin MnTe monolayer films on Fe(001) combined with DFT calculation

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Low-dimensional metallic materials epitaxially grown exhibit distinct properties from bulk materials. It is widely known that Mn deposited on Fe(001) exhibits interlayer antiferromagnetism, and recently, it has been predicted that MnTe thin films also demonstrate a magnetic phenomenon called Altermagnetism [1][2]. In this study, we explored the possibility of realizing Mn monolayers without alloying or mixing using the chalcogen element Te. Te and Mn monolayer films were stacked on Fe(001) substrates, and atomic structures were investigated using ultrahigh vacuum scanning tunneling microscopy (UHV-STM). Electron structure measurements were conducted using scanning tunneling spectroscopy (STS) to identify the alloying between Mn, Te, and Fe.

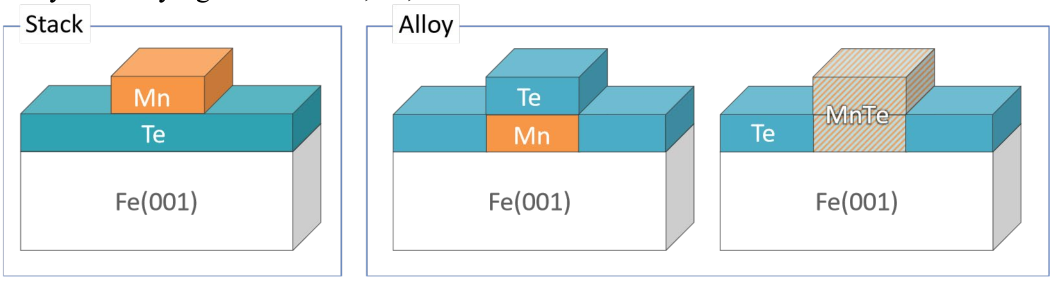

Figure 1: Simplified models of stack and alloy in the system of Mn/Te/Fe(001).

When Te (purity 99.9999%) was deposited to a thickness of 134 pm on a cleaned bccFe(001) whisker at room temperature, monolayer-height Te nanoislands were observed on the Fe(001) surface. The deposited samples were subsequently post-annealed at temperatures ~611 K. STM measurements revealed island growth with increasing post-annealing temperature. The observed Te islands had a height of approximately 160 pm and were found to have a bcc structure. STS measurements showed local density of states (LDOS) peaks of the Te film at positions near the Fermi level at -1.1 eV, -0.3 eV, +0.3 eV, +0.7 eV, and +1.3 eV.

From these results, it was determined how much Te needed to be deposited on the Fe surface to form a certain number of layers. Accordingly, Te was deposited to a thickness of 240 pm and post-annealed at 611 K, resulting in the creation of exactly one monolayer (1 ML) of Te film on the Fe(001) surface. Subsequently, Mn (purity 99.999 %) was deposited onto the Te film at room temperature to a thickness of 46 pm, without thermal diffusion, resulting in numerous islands of Mn being observed (approximately 0.35 MLs of Mn). From the height histogram of the STM shape image, it was found that about 80% of Mn showed heterogeneous alloying. The remaining 20% of Mn formed Mn islands (approximately 160 pm) on the Te monolayer. The Te terraces and Mn islands showed differences in dI/dV maps. Normalized dI/dV curves showed an LDOS peak at +1.3 eV for both Te regions and Mn islands on Te, with Te exhibiting higher intensity.

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Magnetic properties of the epitaxial thin films of Fe_xSn_y

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Magnetic compounds having kagome lattice attract a wide attention in the field of condensed matter physics due to their unique magnetic and electronic properties related to the non-trivial spin arrangements and the electronic structure that hosts Dirac cones and flat bands [1][2]. Intermetallic compounds Fe_xSn_y are layered materials made up of layers of iron and tin atoms arranged on the kagome lattice sandwiched between the two-dimensional tin layers (stannene). Depending on the sequence of the layers, the crystals can have e.g. Fe_3Sn_2 stoichiometry being ferromagnetic at room temperature or FeSn, being antiferromagnetic. The Fe_xSn_y intermetallics have been studied relatively extensively as bulk crystals, but much less is known on their properties in the thin film form [3][4]. The thin films are attractive because the choice of a particular substrate can affect the strain experienced by the films and therefore modify their properties. The thin films grown on the insulating or semiconducting substrates can be also used in magneto-transport experiments which is crucial for future applications.

We prepared the Fe_xSn_y epitaxial thin films on MgO(111) and InSb(111) using molecular beam epitaxy in an ultrahigh vacuum (UHV) system. Directly after growth, crystalline order and stoichiometry were measured using low energy electron diffraction (LEED) and x-ray photoelectron spectroscopy (XPS). Subsequently, the samples were capped by MgO protective layers for the ex-situ measurements: conversion electron Mössbauer spectroscopy (CEMS), magneto-optic Kerr effect (MOKE) and magnetic force microscopy (MFM). The magnetic domain structure was also measured in the Solaris synchrotron in Krakow using photoemission electron microscopy (PEEM). In our contribution we will discuss the effect of the growth parameters and stoichiometry on the magnetic properties of epitaxial Fe_xSn_y thin films. We believe that Fe-based stannides prepared in thin film form will be useful for the future spintronic applications.

This research was funded by National Science Centre, Poland (NCN), grant number 2022/46/E/ST3/00184.

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Effect of helium ion irradiation on spintronic multilayers thin films tacks under different substrates

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The magnetic properties of Pt/Co/Mx/Pt [1] multilayers, with Mx representing various capping materials, are particularly crucial for spintronic devices, emphasizing perpendicular magnetic anisotropy (PMA). Achieving robust PMA [2] on flexible substrates is essential for applications in wearable devices and health monitoring. However, a comprehensive investigation into the impact of diverse stack deposition and modulation conditions on the film's magnetic properties is lacking. In this study, we explore the magnetic characteristics of Pt/Co/RuO2/Pt structures deposited through sputtering on different hard and flexible substrates, with variations in layer thickness, buffer layer deposition temperatures, and capping layers. Our findings reveal variations in coercive field and magnetic dynamic behavior influenced by these factors. Moreover, depositing the buffer layer at elevated temperatures effectively modifies the crystalline state of the films, influencing their performance. To break the symmetry of Pt/Co/Pt, various thin film materials are introduced between Co and the Pt capping. Additionally, we investigate the impact of light He+ ion irradiation on the defects and magnetic parameters of Pt/Co/Pt. Optimizing these conditions is expected to achieve ultra-fast magnetic moment switching, reducing device power consumption. Experimental results indicate that optimized film conditions also enable strong PMA on flexible substrates, providing insights into the magnetic properties of these structures and their potential for wearable and other spintronic devices.

Conclusion

In summary, we utilized Pt/Co/RuO2/Pt-based structures to develop spintronic devices compatible with both hard and flexible substrates. Systematically studying the influence of various conditions (such as thicknesses of the buffer-capping layer and magnetic layer, substrates, deposition temperatures of the buffer Pt layer, and He+ irradiation) on the magnetic properties of our structures, we demonstrated that the magnetic properties change with different conditions. Notably, we established that the films' performance can be modulated by altering the deposition temperatures of the buffer Pt layer. To understand the magnetic switching characteristics, we observed the magnetic dynamics of the films directly using a magneto-optical Kerr microscope, providing insights into the mechanism of domain wall motion. In our detailed exploration of the structure, we successfully deposited strong perpendicular magnetic anisotropy (PMA) samples at room temperature on flexible substrates with ultra-thin Co layers, resulting in outstanding magnetic properties. Our work serves as a comprehensive reference for researchers and represents a crucial step in combining spintronics with flexible devices.

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Understanding the magnetic properties of ultrathin BiYIG grown by sputtering

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Ferrimagnetic insulator thin film garnets with perpendicular magnetic anisotropy have recently expanded the realm of experimental possibilities in magnonics (e.g., [1]). Even though several rare-earth doped and substituted garnet compositions (from Ce to Tm) have been investigated for their perpendicular magnetization, thin films of LuIG [2], YIG [3] and Bi-doped YIG (BiYIG) [4] remain the only compositions enabling a damping in the 10^{-4} range, required for many types of experiments. Among these low-damping garnets, perpendicular magnetic anisotropy has been more practically achieved with BiYIG.

We cover in this contribution our recent progress in the growth by magnetron sputtering of ultrathin BiYIG films with tunable magnetic anisotropy and low damping. The thickness of BiYIG investigated in this work ranges within 3-30 nm. We study the degree of crystalline perfection, the strain, the elemental composition, and its thickness dependence, as well as the dynamic magnetic properties of BiYIG, by X-ray characterization, TEM imaging, analytical techniques in SEM and TEM, ferromagnetic resonance measurements and non-local magnon transport experiments. We relate the evolution of these properties to deposition parameters, such as sputtering gas mixture and deposition power, in the aim of providing useful guidelines for future works with this system.

As expected from strain-related magnetocrystalline anisotropy and growth-induced anisotropy under epitaxial conditions, the choice of the substrate [4] and deposition conditions [5] allow to tune the magnetic anisotropy with precision across the magnetic reorientation. We find that the sputter-grown films differ from films grown by pulsed laser deposition in several aspects. This establishes BiYIG as an ideal platform to combine studies relating to spin-pumping, incoherent spin-waves diffusion and coherent spin-waves propagation, while almost continuously tuning the magnetic parameters, which we demonstrate by a few examples.

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Investigating Magnetic Materials on the nm Scale Using Atomic Force Microscopy

Alexander Klasen, **Andrea Cerreta**

Present and future high-end devices require a combination of functional properties on progressively miniaturized structures. It becomes increasingly crucial to probe these properties, such as the topology of wafer surfaces, the local response of magnetic materials, or the surface potential of 2D heterostructures, on the nanometer-sized architecture of microchips.

In this talk, we demonstrate the use of several state-of-the-art modes of the broad family of Atomic Force Microscopy (AFM) for such applications. Among them, Magnetic Force Microscopy (MFM) is a well-suited tool for analyzing the local magnetic texture. We present several approaches of conducting MFM measurements and provide representive examples from literature ranging from data storage devices to skyrmion host materials. Moreover, it will be explained how Kelvin Probe Force Microscopy (KPFM) is a valuable tool e.g. to study local perturbances in the electronic structure of surfaces and how it can be combined with MFM to reduce the influence of electrostatic crosstalk on MFM measurements. This talk emphasizes the versatility of AFM-based techniques to provide a comprehensive analytical toolbox for various types of samples.

Spin pumping modes in α-Fe_2O_3/Pt bilayers

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[c] Institute for Materials Research, Tohoku University, Japan
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Spin pumping effect is a conversion phenomenon from magnetization dynamics to a conduction electron spin current. It is well understood both theoretically and experimentally in ferromagnetic systems. On the other hand, spin pumping effect and the electrical detection of the antiferromagnetic dynamics has only recently been reported in MnF_2 [1], Cr_2O_3 [2], and so on. While multiple magnetic sublattices in antiferromagnets often result in complex antiferromagnetic dynamic modes, it has not been clear whether some of those modes induce the non-zero spin pumping effect depending upon how the spin mixing conductance is considered [3].

In this study, we focus on the resonance modes in a α-Fe_2O_3 30nm/Pt 4nm bilayer and investigate the spin pumping effect induced by two of the antiferromagnetic dynamic modes in α-Fe_2O_3. The magnetic resonance of α-Fe_2O_3 was excited by sweeping an external magnetic field while irradiating with continuous electromagnetic waves of a constant frequency 100 ~ 200 GHz, generated by a gyrotron [4], which is high enough to access both of the two resonance modes. Voltage induced by a combination of the spin pumping effect and the inverse spin Hall effect was then measured between the ends of the bilayer sample. The measurement temperature was varied from 50 ~ 300 K.

As shown in Figure 1, a voltage peak was observed and shifted to higher field with increasing the frequency, which is consistent with one of the resonance modes of α-Fe_2O_3 [5]. This mode is persistent while varying the temperature across the Morin temperature (T_M) of the α-Fe_2O_3. The other dynamics mode, which is expected to emerge around T_M does not show any voltage peaks, which suggests that the mode is inert to the spin pumping effect. In the presentation, we will discuss in more detail the mechanism of the spin pumping effect induced by the antiferromagnetic dynamic modes of α-Fe_2O_3.

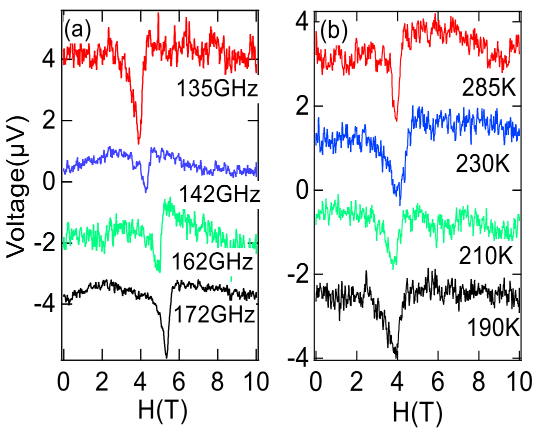

Figure 1: Voltage as a function of magnetic field at room temperature with different frequencies (a) and at different temperatures with 135 GHz (b).

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Spin injection through ferromagnet/antiferromagnet oxide heterostructures

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The development of next-generation spintronic devices requires achieving both efficient spin current injection and a high spin-charge interconversion efficiency. So far, impedance matching and spin−orbit coupling are two important well-known factors in spin current transport in ferromagnetic and nonmagnetic (FM/NM) heterostructures and well-engineered interfaces can facilitate efficient spin transfer. At this point, the insertion of antiferromagnets (AF) has aroused great interest, not only because of the possible implications on the properties of the interface, but also because of the occurrence of magnon-mediated spin currents, which can propagate in both conducting and insulating FMs and AFs. In fact, robust spin transport in the AF insulator NiO has been reported recently. However, the mechanisms responsible for spin transport in AF insulators are not clearly stablished yet. In particular, the role played by the crystalline nature (polycrystalline or epitaxial) of the AF is highly controversial.

In this we present our results on the Inverse Spin Hall Effect in $La_{1-x}Sr_xMnO_3$/NiO/Pt heterostructures as a function of the thickness of the antiferromagnetic NiO layer. Samples have been grown by rf sputtering and characterized by means of advanced X-ray diffraction. We will discuss the influence in spin propagation of the interfacial quality through the heterostructure and the role of NiO thickness.

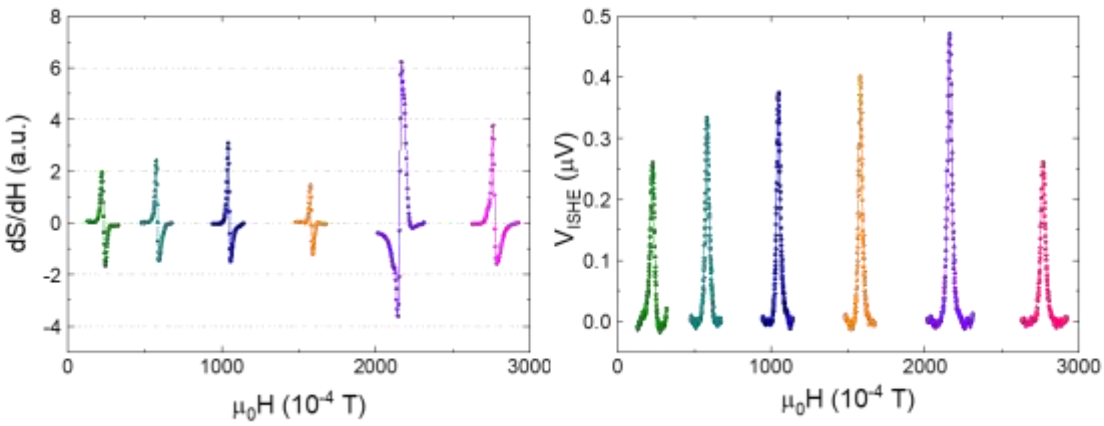

Figure 1. (left) Ferromagnetic resonance and (right) Inverse Spin Hall Effect measured in a LSMO(15nm)/NiO(1nm)/Pt (5nm) heteroestructure at 300K. Measured frequencies are 3, 5, 7, 9, 11 and 13 GHz.

The authors acknowledge financial support from the Spanish Ministry of Science and Innovation through Severo Ochoa (CEX2019-000917-S) and OXISOT (PID2021-128410OB-I00) and Serbian Ministry of Education, Science and Technological Development.

Interfacial Perpendicular Magnetic Anisotropy of Ultrathin Fe(001) film Grown on CoO(001) Surface

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Interfacial perpendicular magnetic anisotropy (iPMA) in magnetic thin films plays a pivotal role in advancing spintronics devices, aiming to realize high-density and low-switching-power magnetoresistive random-access memory (MRAM). While iPMA has been extensively studied in various systems with ferromagnetic (FM) materials, such as Co/Pt, CoFeB/MgO and Fe/MgO, investigations into systems with different magnetisms have been restricted to Fe/NiO [1] until now, where NiO is an antiferromagnetic (AFM) material with out-of-plane AFM spins grown on the MgO(001) substrate at room temperature (RT). And the interaction of domains between two layers remains elusive.

CoO is a typical collinear antiferromagnet with in-plane AFM spins grown on the MgO(001) substrate. In this study, we observed the PMA of an ultrathin Fe(001) layer grown on a CoO(001) film on the MgO(001) substrate at RT as shown in Fig. 1(a). Through quantitative measurements with varying Fe thicknesses (d_{Fe}), we confirmed the interface origin of PMA and identified the spin reorientation transition (SRT) of Fe with a critical d_{Fe} of ~ 0.95 nm at RT, as illustrated in Fig. 1(b). The energy of interfacial PMA at temperatures above (340 K) and below (300 K) the Néel temperature of CoO (~315 K) were calculated to be almost identical of about 1.38 ± 0.01 erg/cm^2, indicating that the PMA of Fe is independent of the antiferromagnetism of CoO. Further analysis through angular-dependent XMCD measurements revealed that the origin of PMA lies in the orbital magnetic moment anisotropy of Fe.

Furthermore, we explored the coupling between FM domains of Fe and the underlying AFM domains of CoO utilizing XMCD- and XMLD-PEEM. FM domains near SRT exhibit a stronger coupling with AFM domains compared to the FM domains with stronger PMA, as shown in Fig. 1(c). This observation was also supported by concurrently imaging FM and AFM domains using polar-MOKE and the magneto-optical birefringence effect, respectively.

Our experimental study not only establishes a new system with PMA based on a ferromagnet/antiferromagnet heterostructure but also explores the interaction between the two layers, providing a novel and promising platform for future research in new physics and spintronics devices.

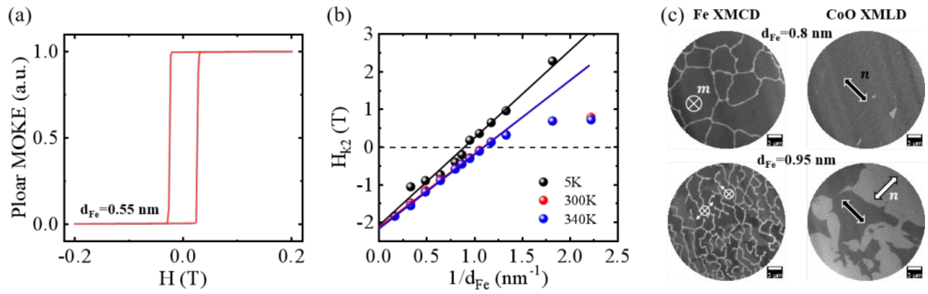

Figure 1. (a) The typical polar-MOKE loop for 0.55 nm Fe layer grown on CoO(001) surface. (b) Uniaxial anisotropy field plotted against $1/d_{Fe}$ at different temperatures. (c) Fe and underlying CoO domains with different Fe thicknesses imaged by XMCD-PEEM and XMLD-PEEM.

[1] Soki Kobayashi, Phys. Rev. Appl. **19,** 064005 (2023).

A magnonic Rowland spectrometer using curvilinear transducers

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This work presents the design, fabrication, and characterization of a spin-wave-based spectrometer - a magnonic device exploiting the interference of spin-wave wavefronts - combined with an RF I/O circuit board. The device is the first to be realized and measured using both, time-resolved MOKE (trMOKE) measurements and electrical pick-up loops, as proposed in the original design in [1].

We use sputtered Yttrium-Iron-Garnet (YIG) thin films to fabricate Rowland circles as islands on a Gadolinium-Gallium-Garnet (GGG) substrate. Between sputtering and recrystallization, we use wet-chemical etching of the amorphous YIG film to achieve micron-sized concave gratings while maintaining low damping. In a subsequent lithography step, we produce curved transducers for homogeneous input and micron-sized loops as localized output transducers. This fabrication technology allows us to bypass the limitations of an earlier design that our group demonstrated in [2]. In particular, using curvilinear transducers, we can circumvent non-linear spin-wave excitation.

In our work we show in-depth characterization using trMOKE during the design phase and precise electrical measurements for device characteristics. The latter comes with the challenge of connecting the magnonic device with the RF I/O system on a circuit board. Therefore, we build on our existing boards and extend their functionality using a matching network [3] for the inputs and propose a possible read-out scheme. To explore the capabilities of the device, we characterize its frequency selectivity and sensitivity, i.e., the spatial separation of focusing points depending on the non-linear spin wave dispersion [1].

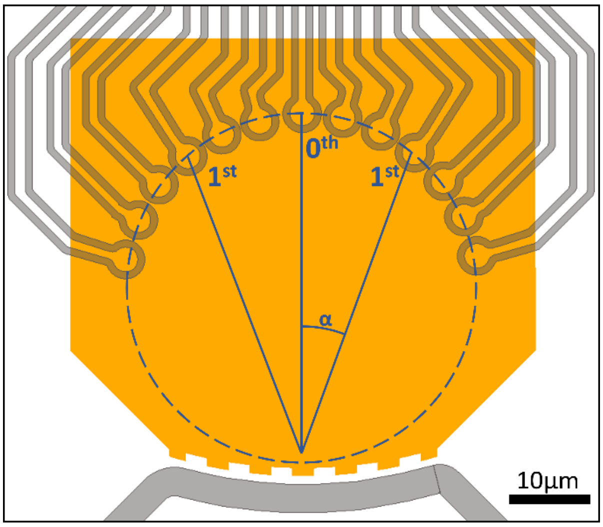

Fig. 1: Schematic overview of a concave grating used as a spin-wave spectrometer. A curvilinear transducer ensures homogeneous excitation of spin waves at the grating. In the forward-volume configuration, wavefronts propagate isotropically and interfere such that focusing points along the Rowland circle appear. The deflection α depends on the spin wave wavelength. The loop antennas are localized pick-ups encircling the focusing points. Unlike the original design in [1], we extend the YIG islands on all sides to avoid reflected waves disturbing the intended interference.

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Surface acoustic waves-driven magnon spin Hall effect in atomically thin van der Waals antiferromagnets

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Intrinsic magnetism in two-dimensional (2D) materials had long been believed to hardly survive due to the enhanced thermal fluctuations. However, the recent discovery of exfoliated van der Waals (vdW) magnets has opened up a new avenue for 2D magnetism at finite temperatures [1,2]. Especially, transition metal phosphorus trichalcogenides are a family of easily exfoliatable vdW antiferromagnets [3]. These materials share the same honeycomb structure, but the bulk antiferromagnetic (AFM) phase varies depending on the magnetic elements. Furthermore, antiferromagnets exhibit ultrafast dynamics, null stray field, and robustness against external fields. Therefore, the investigation of these materials paves the way toward not only the understanding of 2D magnetism, but also future AFM spintronic devices.

Standard methods such as magnetization measurements and neutron diffraction, which could only access macroscopic magnetic properties, are not suitable for the study of atomically thin magnets. Especially, antiferromagnets do not have net magnetization, magneto-optical Kerr effect is not available either. Although recent studies have focused on Raman spectroscopy [4] and second-harmonic generation [5] to detect crystal symmetry lowering associated with the AFM transition, these signals do not provide clear identification in the monolayer limit. Therefore, an inclusive method which suits for exploring 2D antiferromagnets is highly desired.

Here, we propose a magnon spin Hall current driven by the surface-acoustic waves (SAWs) as a novel probe for such 2D vdW antiferromagnets [6]. Owing to extremely large mechanical flexibility of 2D materials, SAWs are ideally suited for fundamental research of them. A modulation of exchange energies due to strain mimics the role of gauge fields for magnons. The strain gauge fields work at two valley points in the opposite direction, leading to the activation of the valley degrees of freedom (DOF). Therefore, the valley DOF with the use of SAWs is a promising concept for detection of the magnetic order in 2D vdW antiferromagnets.

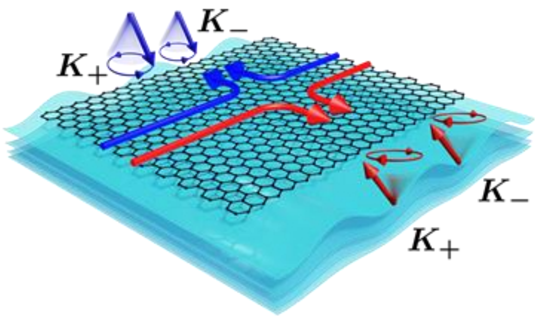

Figure 1: Schematics of acousto-magnonic Hall effect. Both the strain-induced electric fields and the magnon Berry curvature work at the two valley points in the opposite direction respectively, leading to a net spin Hall current.

[1] C. Gong *et al.*, Nature **546**, 265 (2017)
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[3] K. Du *et al.*, ACS Nano **10**, 1738 (2016)
[4] J. Lee *et al.*, Nano Lett. **16**, 7433 (2016)
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[6] **R. Sano** *et al.*, arXiv:2305.13375 (2023)

Towards switchable magnetic tunnel junctions based on two-dimensional polyoxometalates monolayer

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New functionalities emerging in the 2D limit, such as 2D materials or interfaces, are nowadays explored for spintronic devices. For example, organic/inorganic materials down to the monolayer limit are promising to engineer interfaces in magnetic tunnel junctions (MTJs) at the atomic scale. Indeed, to exploit new phenomena occurring at interfaces, 2D hybrid interfaces can be established by combining a ferromagnetic material with a monolayer of molecules. Actually, thanks to the spin-dependent hybridization at ferromagnet/molecule interface, spin polarization and thus tunnel magnetoresistance (TMR) can be controlled [1]. Integrating molecules in MTJs is attractive due the ability to control their properties by chemical design. Indeed, molecular engineering of 2D interface can be realized by changing anchoring group, body and head of molecules to adjust the coupling strength of both ferromagnetic electrodes independently. However, up to now, only passive molecules such as alkane chain or aromatic rings have been integrated into MTJs [2-3]. Despite TMR signals showing the viability of such devices, the electronic properties of these hybrid interfaces cannot yet be controlled *in-situ*.

In this presentation, we will present molecular MTJs integrating complex molecules, called “active” molecules, which can be switched by an external stimulus (light, pressure, electric field…). The energy gap/coupling strength to the electrodes depending on the molecule state and the spin polarization of the interface can be hence modulated. Consequently, MTJs properties are expected to be tuned by switching the molecule. Among the large variety of these “active” molecules [4], electrically addressable molecules are particularly interesting for future applications. Here, we focus on polyoxotungstate ($PW_{11}O_{40}(SiC_3H_6SH)_2$) redox switchable molecules, from the polyoxometalate (POM) family [5]. We will first present the multiple challenges we have faced to fabricate NiFe/POMs/Co MTJs (see Fig.1). Next, we will show the characterizations (XPS, Raman, …) of the interface which confirm the grafting of molecules onto the electrodes. We will then focus on the investigation of the electrical switching of the molecules by conductive-tip AFM. Finally, we will present the preliminary electrical characterization of the NiFe/POMs/Co MTJs which demonstrate that switchable 2D polyoxometalate monolayer can be successfully integrated in MTJs. This opens the way to develop multifunctional spintronic devices.

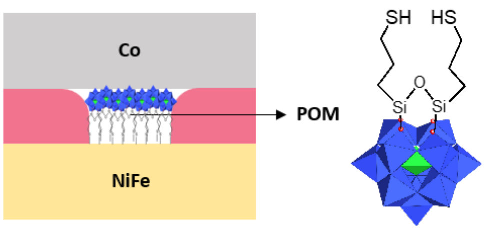

Figure 1: Representation of a MTJ integrating POM molecules

[1] C. Barraud et al., Nat. Phys. 6, 615 (2010)
[2] J. R. Petta et al., Phys. Rev. Lett., 93, 136601 (2004)
[3] M. Galbiati et al., Adv. Mater. 24, 6429 (2012)
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Wavevector-resolved electrical spectroscopy of propagating spin wave based on flip-chip technique

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Spin waves, or magnons in the magnetic thin film have collected high attention due to their potential as an information carrier of future low-power computing devices [1]. To realize the spin wave-based devices, an electrical, coherent excitation and detection of the propagating spin wave is essential. One of the general methods to perform it is the propagating spin wave spectroscopy (PSWS) measuring the microwave transmission between a pair of coplanar waveguide (CPW) antennae deposited on the magnetic film [2]. This procedure allows us to obtain the dispersion relation of the spin wave, between the resonant frequency and external magnetic field, but the characteristic of the wavevector of the excited spin wave is defined by the structure of the antennae, therefore in the measurement, the wavevector resolution is limited. Here, we demonstrate a wavevector-resolved electrical spectroscopy of the propagating spin wave using a flip-chip technique which doesn't require direct deposition or any modification of the magnetic thin film. The spin wave antennae are deposited and patterned on high resistivity Si/SiOx substrate using a 100 nm-thick gold layer, and various magnetic thin films such as Yttrium Ion Garnet (YIG), Permalloy (Py), CoFe, and CoFeB-based synthetic antiferromagnet (SAF) are simply placed on top of the antennae. We observed spin wave transmission magnitude loss as around -4.5 dB compared to the conventional PSWS technique in which the antennae are directly deposited on the magnetic film, originating from an additional distance between the antennae and the magnetic film [3]. Using this flip-chip-PSWS technique, we perform multiple spin wave transmission measurements for the same magnetic thin film with various antennae structures designed for a diverse range of wavevectors. Combining the spectrums of the resonant frequency to the field for each wavevector, we obtained the dispersion relation of the propagating spin wave, between the frequency and the wavevector of the magnetostatic surface spin waves (MSSWs) and the backward volume spin waves (BVSWs). Our suggested technique of flip-chip-PSWS can provide us with not only more freedom in the use of scarce or vulnerable samples such as Van der Waals materials but also an efficient way to electrically measure the spin wave dispersion relation in the wavevector domain that has been only performed optically so far, such as using the Brillouin light scattering.

This work was supported by the National Research Foundation of Korea (NRF) funded by the Korean government (MSIP) (Grant No. RS-2023-00275259).

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[2] V. Vlaminck *et al., Science* **322**, 410 (2008)
[3] T. Devolder, *Physical Review Applied* **20**, 054057 (2023)

Enhancement of antiferromagnetic stability by adsorption of molecular layers

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The tuning of the properties related to electron spin in materials is an important aspect for the design of performing devices and complex logic in spintronics. In this regard, organic molecules interfaced with different classes of materials were demonstrated to be capable of influencing their spin transport and magnetic properties [1, 2]. In this work, we present the results of the combination of antiferromagnetic layers and organic materials with a focus on the modification of the magnetic behaviour of the system. We show that the adsorption of C60 (buckminsterfullerene) and Gaq3 (Tris(8-hydroxyquinoline) gallium) on an antiferromagnetic CoO granular thin film can efficiently manipulate its blocking temperature. We demonstrate in an exchange bias structure with an additional ferromagnetic Co layer that both the exchange bias field and coercivity are enhanced. These effects are attributed to a significant improvement in the stability of the antiferromagnetic layer.

Ab initio calculations for CoO/C60 indicate that the molecular adsorption is responsible for a charge redistribution on the CoO layer that alters the occupation of the d orbitals of Co atoms and, to a smaller extent, of the p orbitals of oxygen. As a result, the AF coupling parameters are modified. Considering the granular nature of CoO, the larger AF stability upon molecular adsorption is associated then with a larger number of AF grains that are stable upon reversal of the Co layer. The interfacial nature of this effect is demonstrated by considering CoO layers of various thicknesses.

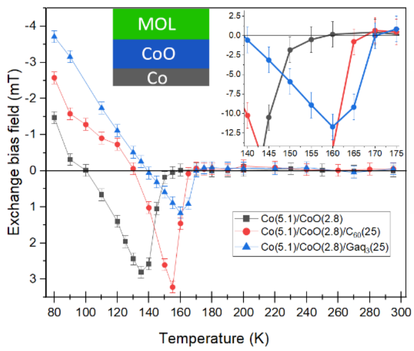

Figure 1: Temperature dependency of exchange bias field for Co/CoO samples interfaced with Gaq3 and C60 molecular layers

[1] V. Dediu et al. *Nature materials* 8.9 (2009): 707-716

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Oscillation between acoustic and optic magnon in synthetic antiferromagnets

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Recently, hybridized systems between two quasi particles, such as photon-magnon [1] and phonon-magnon [2] or magnon-magnon have been attracting much attention in the field of spintronics. Magnons in in-plane magnetized synthetic antiferromagnets have two resonance modes ; an acoustic mode and optical mode, corresponding to the in-phase and out-of-phase precession in two magnetizations, respectively. Previously, we demonstrated dipolar-mediated magnon-magnon coupling between acoustic and optic magnons depending on the angle of direction of applied in-plane magnetic field in in-plane magnetized synthetic antiferromagnets [3, 4]. In this study, we investigate magnetic dynamics of magnon-magnon coupling between acoustic and optic magnons in in-plane magnetized synthetic antiferromagnets by using micromagnetic simulation. The micromagnetic simulation is performed utilizing mumax3 [5]. Cell size of 50 × 50 × 15 nm is used for calculation which is much smaller than the wavelength of excited magnetostatic spin waves. The sample shape is 400 μm × 10 μm × 30 nm. The magnetic moments in the two layers are antiferromagnetically coupled. The magnetic field (750 Oe) is applied to the direction 45° away from the propagation direction of spin waves. Magnons are excited by applying single pulse of in-plane magnetic field with pulse width of 10 ps along longitudinal direction of the sample. We simulate spin dynamics of excited magnons for 10 ns at 1 ps intervals. Figure 1 shows time dependence of the amplitude of Fast-Fourie-transformation (FFT) of magnetic dynamics for spin waves with a specific wave number *k*' = 0.419 rad/μm, obtained by Fourie-transformation analysis. We find that FFT amplitude of spin waves in two magnetic layers oscillates depending on the time. In the presentation, we will show more detailed analysis results and discuss them.

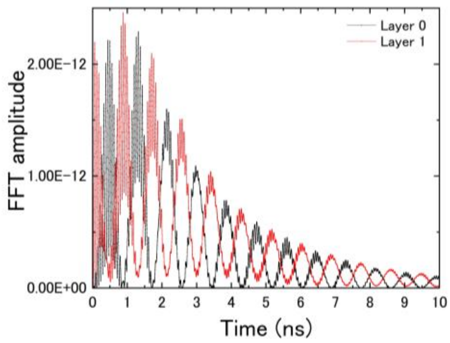

Figure 1: Time dependence of FFT amplitude for spin waves with wave number *k*' = 0.419 rad/μm.

[1] X. Zhang *et al.*, Phys. Rev. Lett. **113** (2014), 156401.

[2] T. Hioki *et al.*, Communications Physics **5** (2022), 115.

[3] Y. Shiota *et al.*, Phys. Rev. Lett. **125** (2020), 017203.

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Effects of Mn monolayer insertion in spin-transport properties of Fe/MgO/Fe and Co/MgO/Co magnetic tunnel junctions

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A magnetic tunnel junction (MTJ) with a smaller resistance-area (RA) product, and a high value of tunnelling magneto resistance (TMR) ratio which has a weaker temperature dependence are desirable for its technological applications. A large TMR ratio at the cryogenic temperature has already been reported owing to the coherent tunneling of electrons with Δ_1 symmetry in Fe/MgO/Fe and related systems [1,2]. However, thermal fluctuation of interfacial magnetic moments results in a stronger temperature dependence of TMR ratio [3]. Recently, a reasonably high TMR ratio of 350% (1002%) are reported at room (low) temperature with *bcc*-CoMnFe electrode for MgO-based MTJs [4]. Based on the structural analysis it was found that Mn tends to form the interface with MgO [4].

Using *ab-initio* calculations we discuss the impact of insertion of Mn-monolayer at the interfacial region of conventional *bcc*-Fe/MgO/*bcc*-Fe and *bcc*-Co/MgO/*bcc*-Co MTJs. We find that RA-product is reduced in the cases *X*/Mn(1ML)/MgO/Mn(1ML)/*X* (*X*=Co, Fe) MTJs compared to the pristine *X*/MgO/*X* MTJs, while TMR ratio remains in the order of 1000%. However, formation of MnO layer at the interface remarkably degrades the spin-transport properties because of much reduced conductance in parallel magnetization configuration as illustrated in Figure 1. Furthermore, we discuss the interfacial electronic structure, magnetism, and temperature dependence of TMR ratio in terms of magnetic anisotropy energy and interfacial exchange stiffness. This work was partially supported by JST CREST (No. JPMJCR17J5) and XNICS (No. JPJ011438). The authors thank S. Mizukami for fruitful discussions.

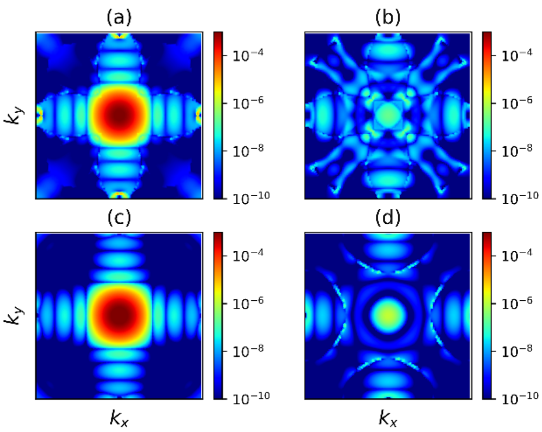

Figure 1. In-plane wave-vector dependence of majority-spin conductance (in e^2/h) in parallel magnetizations for (a) Fe/Mn(1ML)/MgO/Mn(1ML)/Fe, (b) Fe/MnO(1ML)/MgO/MnO(1ML)/Fe, (c) Co/Mn(1ML)/MgO/Mn(1ML)/Co, (d) Co/MnO(1ML)/MgO/MnO(1ML)/Co MTJs.

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Modification of three-magnon splitting by in-plane magnetic fields

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Over the past few decades, extensive research has been conducted on magnetic vortices due to their fundamental physical properties and potential applications as magnetic storage devices or resonators. Information can be encoded in the polarity or gyrotropic motion of the vortex core. Moreover, magnetic vortices offer a versatile spectrum of radial and azimuthal modes, which exhibit interesting linear and nonlinear dynamics. One notable example is three-magnon splitting, where one mode can spontaneously split in two secondary magnon modes when excited above a threshold power. Three-magnon splitting follows specific selection rules, with the split modes having distinct frequencies and mode numbers to fulfill energy and angular momentum conservation [1]. Magnetic vortices offer the potential to stimulate these processes below their intrinsic threshold powers [2,3], making them promising candidates for novel computing approaches such as reservoir computing.

In this study, we demonstrate that the application of in-plane magnetic fields in the order of a few mT can efficiently modify three-magnon splitting [4]. Using micromagnetic simulations and Brillouin-light-scattering microscopy, we show that the deformation of the vortex results in additional secondary butterfly modes that follow the same selection rules as the regular modes but exhibit different localization (Fig. 1) and much lower threshold powers for three-magnon splitting.

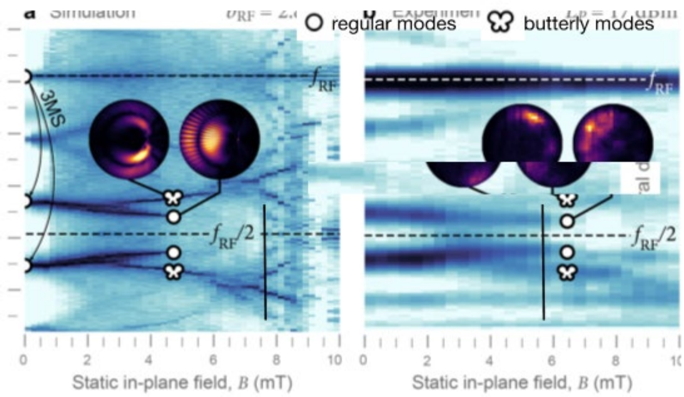

Figure 1: Magnon mode profiles in a displaced magnetic vortex obtained by micromagnetic simulations (top row) and experimentally measured by Brillouin-light-scattering microscopy (bottom row). Figure adapted from [4].

This work has received funding from the EU Research and Innovation Programme Horizon Europe under grant agreement no. 101070290 (NIMFEIA).

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Modification of three-magnon splitting by in-plane magnetic fields

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Over the past few decades, extensive research has been conducted on magnetic vortices due to their fundamental physical properties and potential applications as magnetic storage devices or resonators. Information can be encoded in the polarity or gyrotropic motion of the vortex core. Moreover, magnetic vortices offer a versatile spectrum of radial and azimuthal modes, which exhibit interesting linear and nonlinear dynamics. One notable example is three-magnon splitting, where one mode can spontaneously split in two secondary magnon modes when excited above a threshold power. Three-magnon splitting follows specific selection rules, with the split modes having distinct frequencies and mode numbers to fulfill energy and angular momentum conservation [1]. Magnetic vortices offer the potential to stimulate these processes below their intrinsic threshold powers [2,3], making them promising candidates for novel computing approaches such as reservoir computing.

In this study, we demonstrate that the application of in-plane magnetic fields in the order of a few mT can efficiently modify three-magnon splitting [4]. Using micromagnetic simulations and Brillouin-light-scattering microscopy, we show that the deformation of the vortex results in additional secondary butterfly modes that follow the same selection rules as the regular modes but exhibit different localization (Fig. 1) and much lower threshold powers for three-magnon splitting.

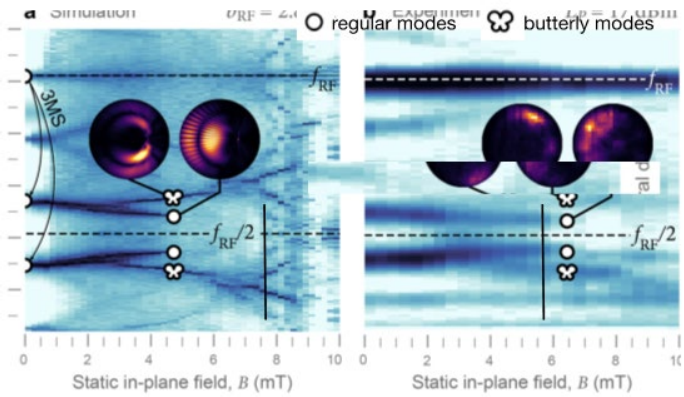

Figure 1: Magnon mode profiles in a displaced magnetic vortex obtained by micromagnetic simulations (top row) and experimentally measured by Brillouin-light-scattering microscopy (bottom row). Figure adapted from [4].

This work has received funding from the EU Research and Innovation Programme Horizon Europe under grant agreement no. 101070290 (NIMFEIA).

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Quantitative evaluation of the coupling between spin wave and surface acoustic wave in NiFe thin films

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Coupling between spin waves (SWs) and surface acoustic waves (SAWs) has been the recent focus in spintronics and phononics. In many cases, magnetoelastic coupling is the dominant coupling [1,2], but in NiFe thin films where the magnetoelastic coupling is minimized, the gyromagnetic coupling is reported to be manifested [3]. However, a quantitative evaluation of the ratio between the contributions of these two couplings has yet to be achieved.

In this study, to quantitatively evaluate the contributions of the two couplings in NiFe thin films, we examined the frequency and magnetic field angle dependences of the SAW resonant absorption due to SW-SAW couplings. As shown in Figure 1(a), by placing two interdigital transducers (IDTs) on a $LiNbO_3$ substrate and connecting each of them to individual ports of a vector network analyzer, we measured the SAW transmission coefficient S_{21}. Figure 1(b) shows a SAW transmission coefficient change ΔS_{21}, corresponding to the SAW resonant absorption, observed in a wide frequency range when a 60-nm-thick NiFe thin film is placed in the middle of the two IDTs and a magnetic field is applied in the SAW propagation direction. Figure 1(c) shows the magnetic field angle dependence of the SAW resonant absorption at the frequency of 3.8 GHz, where the nonreciprocity manifests at finite magnetic field angles.

In the presentation, we will discuss a method to evaluate the ratio between the contributions of magneto-elastic and gyromagnetic couplings in NiFe thin films, based on the results.

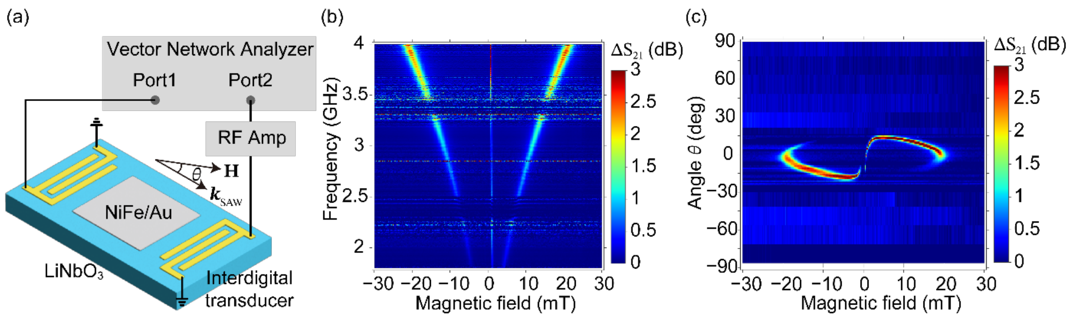

Figure 1: (a) Schematic illustration of the experimental setup. (b) SAW transmission coefficient change ΔS_{21} as functions of frequency and magnetic field strength at an angle of $\theta = 0$. (c) SAW transmission coefficient change ΔS_{21} as functions of magnetic field angle and strength at the frequency of 3.8 GHz.

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Highly sensitive tunnel magneto-resistive sensor with magnetic vortex structure

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Tunnel magnetoresistance (TMR) sensors using magnetic tunnel junction (MTJ) elements are highly sensitive magnetic sensors[1]. This study aims to enhance the sensitivity of a magnetic vortex-type linear TMR sensor by making the small top pinned layer compared with the bottom free layer (Fig.1 (a)). The sensitivity is defined as TMR ratio/2H_s, where H_s is the saturation field of the free layer. Therefore, we can enhance the sensitivity by increasing TMR ratio or reducing H_s. In the previous work, it is demonstrated that in a vortex MTJ, making the pinned layer's diameter 2r_t smaller than the free layer's diameter 2R_b leads to reduced H_s and enhanced sensitivity. The authors used $Ni_{80}Fe_{20}$ (Py) as the free layer material and microfabricated the pinned layer with 2r_t = 2 µm and the free layer with 2R_b = 10 µm. As a result, H_s was reduced from 156 Oe to 31 Oe and the sensitivity was enhanced from 0.85 %/Oe to 4.43 %/Oe [2]. In this study, we further explored the potential for enhancing sensitivity by replacing the free layer material with CoFeSiB expected higher TMR ratio [3] and by reducing the pinned layer's diameter down to less than 1 µm.

We deposited a multilayered MTJ film on a thermally oxidized Si substrate, consisting of Ta(5)/Ru (40)/Ta (5)/CoFeSiB (70)/Ta (0.2)/CoFeB (3)/MgO/CoFeB (3)/TaB (0.1)/CoFe (0.8)/Ru (0.8)/CoFe (3)/IrMn (10)/Ta (2)/Ru (7) (nominal thickness in nm) by magnetron sputtering. Then we microfabricated the film 2R_b = 10 µm and 2r_t = 5–10 µm. TMR properties of the microfabricated films were measured by dc four-probe method.

We observed a hysteresis-free magnetic resistance curves reflecting the magnetization process of magnetic vortex structure (Fig.1 (b)). In addition, a high TMR ratio of 150% at RT was successfully achieved and 2H_S was relatively small. As a result, the sensitivity was ca. 0.9 %/Oe. Since the pinned layer can be formed smaller, vortex-type linear sensors are expected to exhibit higher sensitivity.

This research was supported by the NEDO Leading Research Project, SIP Project, X-nics Project, CSIS, and CIES from Tohoku University.

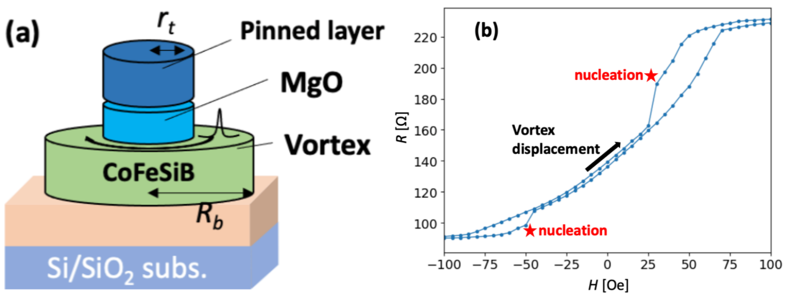

Figure 1: (a) A schematic of the sensor geometry. (b) TMR curve of vortex MTJ with the free layer's thickness of 70 nm, 2R_b = 10 µm, and 2r_t = 5 µm .

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Reconfigurable spin current transmission and magnon–magnon coupling in hybrid ferrimagnetic insulators

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Coherent spin waves possess immense potential in wave-based information computation, storage, and transmission with high fidelity and ultra-low energy consumption. However, despite their seminal importance for magnonic devices, there is a paucity of both structural prototypes and theoretical frameworks that regulate the spin current transmission and magnon hybridization mediated by coherent spin waves. Here, we demonstrate reconfigurable coherent spin current transmission, as well as magnon–magnon coupling, in a hybrid ferrimagnetic heterostructure comprising epitaxial $Gd_3Fe_5O_{12}$ (GdIG) and $Y_3Fe_5O_{12}$ (YIG) insulators. By adjusting the compensated moment in GdIG, magnon–magnon coupling was achieved and engineered with pronounced anticrossings between two Kittel modes, accompanied by divergent dissipative coupling approaching the magnetic compensation temperature of GdIG ($T_{M,GdIG}$), which were modeled by coherent spin pumping. Remarkably, we further identified, both experimentally and theoretically, a drastic variation in the coherent spin wave-mediated spin current across $T_{M,GdIG}$, which manifested as a strong dependence on the relative alignment of magnetic moments. Our findings provide significant fundamental insight into the reconfiguration of coherent spin waves and offer a new route towards constructing artificial magnonic architectures.

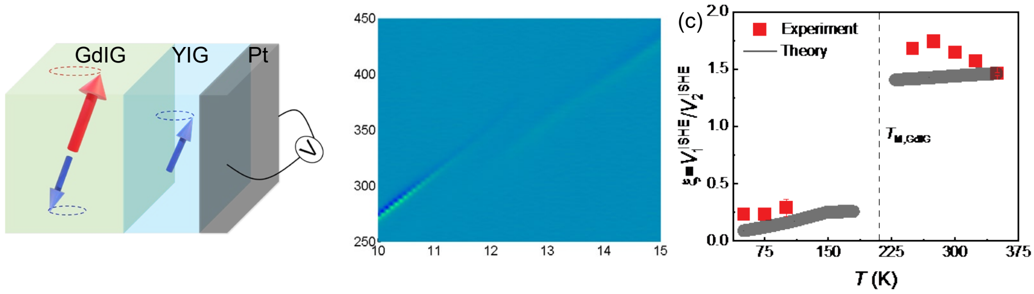

Figure 1 (a) Schematic of magnetization dynamics in the GdIG/YIG/Pt hybrid systems. (b) VNA-FMR spectra ($\partial S_{21}/\partial H$) for GdIG/YIG as a function of magnetic field and frequency at 150 K, revealing magnon-magnon coupling. (c) Experimental ratio of the detected inverse spin Hall voltages at f=6 GHz contributed by the two hybrid modes, along with the corresponding theoretical prediction, plotted as a function of temperature.

Geometry-dependence of magnon-phonon coupling in YIG-GGG platform

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Coherent transduction between magnon and phonon enables the long-range transmission of magnetic excitation and enhances the controllability of a hybrid system via the versatile interaction of magnetic material with external stimuli [1-3]. While the magnetoelastic effect mediates the coupling between magnon and phonon, the interplay of magnetoelastic effect and dispersion relation of dipolar spin waves exhibits characteristic dependence of the magnon-polaron spectra on the direction of the external magnetic field.

In this work, we observe the interaction between high-overtone bulk acoustic waves and various modes of propagating magnetostatic spin waves. We use yttrium iron garnet (YIG) films with different thicknesses on a gadolinium gallium garnet (GGG) to confirm the dependence of magnon-phonon coupling strength on the propagation modes of spin waves. The transition between backward volume spin wave (BVSW) and magnetostatic surface spin wave (MSSW) is achieved by changing the direction of the magnetic field with respect to spin wave propagation direction. The dependence of coupling strength between magnon-phonon appears as the periodicity of the free spectral range, which shifts as the spin wave mode transits from MSSW to BVSW. Next, we introduce a micro-gap in the spin wave propagation path to identify the effect of spatial separation of spin wave medium on the mode-dependent magnon-phonon conversion. From the variation of phonon signature in the spin wave spectra, we observe a phonon-mediated transfer of magnons over the gap. Owing to the difference in coupling strength between magnon and phonon, we extract a varying transfer efficiency for different spin wave modes. Our result suggests a new approach to utilize the YIG/GGG system as a platform for magnon-based hybrid systems and may open a new way to explore the role of phonons in spin wave specific phenomena such as magnon Bose-Einstein condensate and parametric pumping.

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A micromagnetic study of the fractional resonance response driven by voltage-controlled magnetic anisotropy

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Spintronic diodes (STDs) exhibit potential advantages over semiconductor. They are compact (nanoscale size), CMOS-compatible, energy-efficient [1][2]. In particular, the STDs allows to use many driving forces to tune their rectification response, such as the voltage controlled magnetic anisotropy (VCMA) [3]. Here, we have predicted a fractional parametric resonance response driven by the simultaneous excitation of VCMA and ac spin-transfer torque for spintronic diodes working in the passive regime.

This resonance is characterized by the ferromagnetic resonant frequency, the standard parametric excitation at twice the resonance frequency and several other sub-harmonic peaks, all of which are an integer fraction (1/2,1/3, etc.) of the main resonance frequency. We have performed a systematic study of the resonance response of the MTJ as a function of VCMA amplitude. The dynamics is driven by the presence of VCMA and simultaneity by spin-transfer-torque driven by an ac in-plane spin-polarized current density (Jac =0.1MA/cm), and both current density and VCMA have the same frequency.

The figure 1 shows the results that are obtained by considering the current value fixed and varying only the value of VCMA (KVCMA =0, 50, 100 mT). In absence of VCMA, we obtained a frequency resonance of 4.88GHz. With adding of VCMA, not only the same frequency, we obtained other frequencies minor, until to 7for the value of VCMA higher and in this case is present also a peak at twice the ferromagnetic frequency (labelled -1). This work opens a new direction for the use of spintronic diodes in the field of communication, as a single device would have the ability to detect more information carriers.

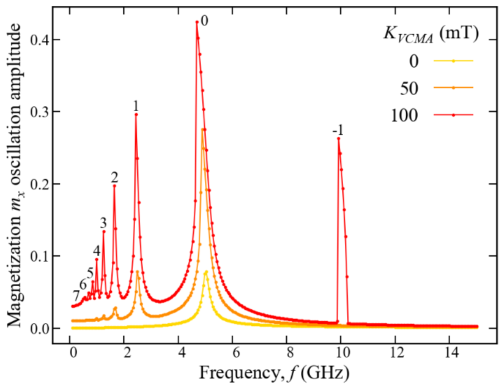

Figure 1: Oscillation amplitude of the x-component of the magnetization mx as a function of the frequency of the ac current density Jac with different values of the VCMA coefficient $KVCMA$.

ACKNOWLEDGEMENTS

This work was supported under the project number 101070287 -- SWAN-on-chip - HORIZON-CL4-2021-DIGITAL-EMERGING-01, by the Italian Ministry of University and Research through the project “SKYrmion-based magnetic tunnel junction to design a temperature SENSor - SkySens” PRIN_20222N9A73_002 and by the PETASPIN association (www.petaspin.com).

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Influence of ferromagnetic coupling in $Fe_{85}Co_{15}$/Py bilayers on the ISHE voltage generated by spin pumping

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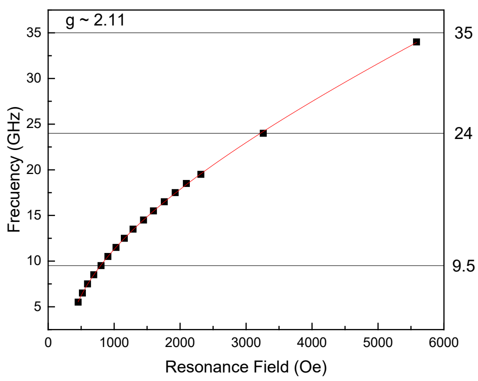
We present a detailed study of ferromagnetic coupling of FM/FM bilayers and its spin transport properties. A series of $Fe_{85}Co_{15}(t)$/Py (5 nm) bilayers, where t = 5, 10, 15, 20 and 25 nm, deposited on MgO substrates [100] were grown using the Sputtering technique. To determine the thickness of the bilayers, X-ray reflectometry and TEM studies were carried out. Magnetic characterization of the samples was performed by using the vibrating sample magnetometer (VSM) and the magneto-optical Kerr effect magnetometer (MOKE). The hysteresis loops reveal the existence of a hard axis of magnetization in the [100] direction of MgO, and an easy one along the [110] direction. Using ferromagnetic resonance (FMR), the angular dependence of the resonance field was obtained at three different frequencies: 9.5 GHz (X-band), 24 GHz (K-band) and 35 GHz (Q-band) and it was fitted within the Smit and Beljers approximation. For lower frequencies than 20 GHz, broad-band FMR experiments were performed using a Vector Network Analyzer, VNA, in order the get a better determination of the dispersion relation (see Figure 1, left panel). Inverse Spin Hall Effect (ISHE) measurements were carried out, in which a much more significant antisymetric component was observed than the symmetric one (see Figure 1, right panel). This effect could be attributed to, the injection of spin current in opposite directions of each ferromagnet, or to other contributions such as the Anomalous Hall Effect (AHE).



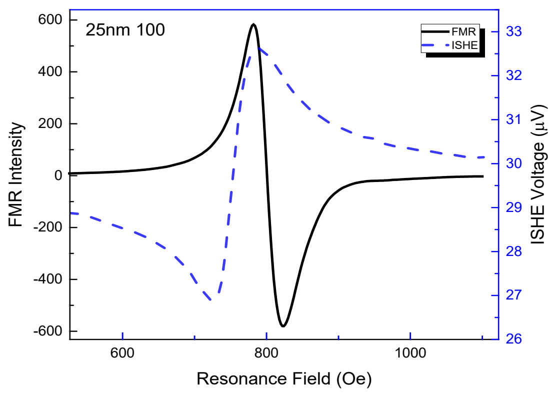


Figure 1: Left panel: Dispersion relation for the FeCo(15 nm)/Py sample. Right Panel: ISHE voltage and FMR signal versus Resonance field for the FeCo(25 nm)/Py sample along the [100] direction.

Reconfigurable magnetic devices with integrated micro-magnets

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Recently the research field of magnonics, aiming to use spin waves (SWs), the collective excitations of ordered magnetic materials, to carry, store and process information, has been rapidly growing due to its potential to develop technologies that enable high-frequency data transmission, in the GHz ranges, while minimizing energy consumption. However, the integration of magnonic devices with traditional electronics faces challenges in providing low-power solutions for application of bias fields to manipulate SWs propagation.

In this work we present a first example of tunable magnonic systems where a local bias field is produced by permanent micromagnets integrated with magnonic conduits. As it can be seen in Fig.1a we fabricated devices, where two permanent SmCo micromagnets are placed symmetrically with respect to a CoFeB magnonic conduit at varying distance *d*. The propagation of SWs, excited in the Damon-Eshbach geometry by using a coplanar waveguide, is investigated by micro-focused BLS measurements, applying an external bias field of 60 mT parallel to the short axis of the conduit. The direction of the external field is reversed to be either antiparallel or parallel with respect to the field produced by the micromagnets. Switching from the antiparallel to the parallel configuration we observed a strong reduction of the SWs propagation distance (Fig.1b,c). Moreover, we find that the effect of attenuation depends on the micromagnet-conduit distance up to become negligible when d=8 μm. Micromagnetic simulations show that this behavior can be explained taking into account that the bias field, produced by the micromagnets, induces a local variation of the internal field in the conduit and a shift in the SW dispersion relation.

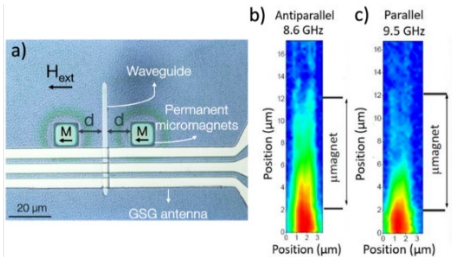

Figure 1 a) Device layout; b,c) BLS measurement of spin wave propagation under antiparallel (b) and parallel (c) alignment between the external field and the bias field generated by the permanent micromagnets.

Acknowledgements
Support from the European Community's HORIZON-CL4-2021-DIGITAL-EMERGING-01 Program, under Grant No. 101070536 MandMEMS is acknowledged. This work was funded by the European Union—NextGenerationEU under the Italian Ministry of University and Research (MUR) National Innovation Ecosystem Grant No. ECS00000041—VITALITY. CUP: Nos. B43C22000470005 and J97G22000170005.

Miniaturized delta-E effect magnetoelectric sensors

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Magnetoelectric sensors based on the delta-E effect utilize the change in the mechanical stiffness tensor of the magnetostrictive material upon applying a magnetic field, which leads to a detuning of the resonance frequency. These sensors have proven the potential to detect magnetic fields of small amplitude and low frequency. It was demonstrated that using sensor arrays with many sensor elements can improve detection limits [1]. However, challenges persist in achieving high spatial resolutions and fabricating compact arrays with mm-sized sensors. Moreover, the release process during the resonator fabrication introduces anisotropic stress into the magnetic layer due to intrinsic stress relaxation in the substrate and other layers, resulting in poor reproducibility [2]. Additionally, the performance of cantilever-type sensors is influenced by the inhomogeneous magnetic properties at their clamping region [3]. Here, we present a shadow mask deposition technology and free-free microresonator design for sub-mm sized delta-E effect magnetic field sensors, aiming to minimize residual stress, ensure homogenous magnetic properties, and enhance reproducibility. Employing displacement measurements and a magneto-mechanical model, residual stress induced by the deposition of the FeCoSiB magnetic layer and its impact on the effective magnetic anisotropy was determined, and a homogenous magnetoelastic anisotropy below 500 J/m^3 was obtained. Magneto-optical measurements are used to analyze the local magnetic behaviors, and the results are compared with simulations. Different resonance modes are identified, and the correlation between the sensitivities and spatial magnetic and mechanical properties in these modes is explored. Signal and noise performance of different sensor geometries are investigated to comprehend the influence of geometry on sensor performance. Finally, high device-to-device reproducibility with a resonance frequency deviation of ≤0.2 % is obtained. Overall, we demonstrate highly reproducible miniaturized delta-E effect sensors using the proposed deposition technique and sensor design. The results represent a significant step towards fully integrated sensor arrays, with the potential for higher spatial resolution and improved detection limits using compact arrays or incorporating flux concentrators.

Funding by the German Research Foundation (DFG) via the CRC 1261 “Magnetoelectric Sensors: From Composite Materials to Biomagnetic Diagnostics” is gratefully acknowledged.

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Current induced magnetization dynamics in multiferroic tunnel junctions

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Contemporary magnetic random access memories (MRAM) utilize magnetic tunnel junctions, which are controlled by spin polarized current (using spin transfer torque - STT). Further development requires current flowing only through the high spin-orbit coupling material neighbouring one of the ferromagnetic electrodes, using spin-orbit torque – SOT.

In the present work, we study the static, dynamic and temperature dependent magneto-transport properties of an Fe/BTO/LSMO and a Pt/Co/BTO/LSMO mutliferroic tunnel junction (MFTJ) with BTO as the ferroelectric barrier. The multilayer structure was grown on a high quality crystalline STO substrate by means of pulsed laser deposition, which enables epitaxial layer-by-layer growth. The measured static properties indicate that the MFTJ has multiferroic properties with the tunnelling magnetoresistance (TMR) present at room temperature (RT) and tunnelling electro-resistance (TER) reaching two orders of magnitude at RT. The magnetization dynamics of Fe and Co was induced by means of STT and SOT, respectively, which can lead to the determination of several important material parameters, such as magnetization saturation, anisotropy energy or damping.

In the Fe/BTO/LSMO trilayers, we observed a ferromagnetic resonance (FMR) signal originating from both the Fe and LSMO ferromagnets, when the rf current is tunnelling via the BTO barrier [1]. On the contrary, in the Pt/Co/BTO/LSMO MFTJ, the rf current flows in the sample plane through the Pt/Co bilayer, which is characterized by a sizable spin-Hall magnetoresistance. The SOT-FMR signal is measured using both two-point (based on SMR) and four-point (based on the anomalous Hall effect) geometry [2]. Surprisingly, at temperatures below RT, the second peak is also present, although the RA product of the BTO tunnel barrier prevents any charge currents from tunnelling. Both the linewidth and the resonance peak evolution with the magnetic field is in agreement with the LSMO dynamics probed with VSM magnetometry. We suggest that the LSMO magnetization dynamics is induced by the RF Oersted field and the signal is picked up by the inverse spin Hall effect in the Pt/Co bilayer.

Further optimization of MRAM as well as the development of spin-orbit-based logic may take advantage of the combination of ferroelectric and ferromagnetic effects in the same material system. Specifically, so-called magneto-electric spin-orbit logic (MESO) [3] requires strong coupling between the ferroelectric polarization of the barrier and the ferromagnetic state of a nanomagnet fabricated on the top of it. Future directions, such as the epitaxial growth of an MFTJ with high spin-orbit coupling materials or the search of new multiferroic materials will be discussed.

The project is supported by Grant No. 2021/40/Q/ST5/00209 from the National Science Centre, Poland and the program "Excellence initiative research university" for the AGH University of Krakow.

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Light-induced magnetic modifications in Ni/$KNbO_3$ multiferroic heterostructure

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During the last years, multiferroic heterostructures, combining ferromagnetic (FM) and ferroelectric (FE) materials interfacially coupled via converse magnetoelectric effects [1,2], offered an important spintronic opportunity thanks to the possibility of modifying the FM response with an external stimulus, for instance an applied bias [3] or via fully optical means [4]. The coexistence of a large number of parameters playing a role in both FM and FE components of the heterostructure, together with the wide variety of materials for both components, leaves room for further implementations, exploiting characteristics up to now neglected.

In this framework, here we report preliminary results from our research on tailoring the magnetic properties of a FM/FE heterostructure by applying UV/visible light irradiation, having deposited Ni thin film on highly photovoltaic $KNbO_3$ single crystals as the FE substrate, a combination up to now unreported. Photovoltaic behavior is measured under illumination with visible light of different wavelengths. Magneto-Optic Kerr Effect (MOKE) measurements proved a ferromagnetic response for Ni films down to 4 nm thickness, sign of a good growth of the FM layer via electron beam evaporation, whose changes under illumination are currently under investigation.

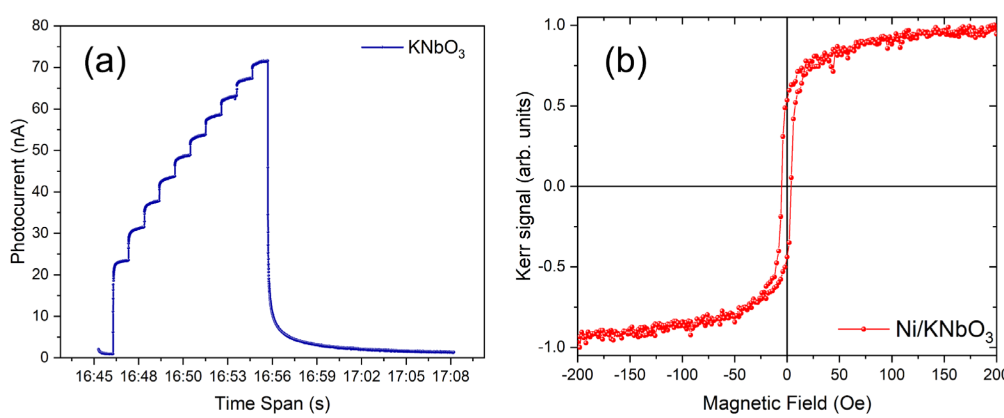

Figure 1: (a) photocurrent measurements of $KNbO_3$ under 405 nm illumination at different fluences; (b) in-plane MOKE hysteresis loop of 4 nm Ni layer deposited on top.

[1] W. Erenstein et al., Nature **442** (2006) 759.
[2] C.A. Fernandes Vaz, J. Mater. Chem. C **1** (2013) 6731.
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Interplay of dipolar and Dzyaloshinskii–Moriya interactions in helicity control of hybrid magnetic skyrmion

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Recently, a type of hybrid skyrmion with intermediate helicity between Bloch and Néel skyrmion, has gained more attraction. It has improved mobility and reduced the skyrmion-Hall effect, which prevents the skyrmions from moving parallel to the current flow. Furthermore, since the hybrid skyrmion can be considered as a superposition of the Néel and Bloch skyrmion, it is also a potential candidate as building blocks for quantum bits (qubits) in quantum computers, where information can be stored by utilizing the helicity degree of freedom

We investigated the stabilization and helicity control of the hybrid skyrmion in a two-dimensional magnetic system using an analytical model and micromagnetic simulation. We look at the interplaying factors of the bulk (D_b) and interfacial (D_i) Dzyaloshinskii–Moriya interactions (DMI) along with the dipolar interaction.

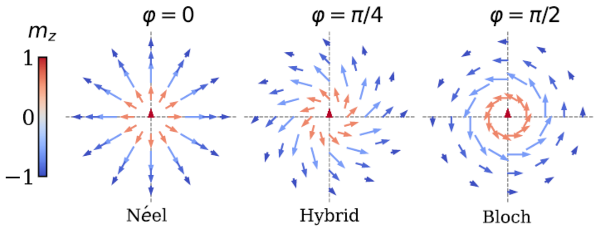

Figure 1. Néel, Hybrid, and Bloch skyrmion with $\boldsymbol{m} = \hat{r}\sin\theta\cos\varphi + \hat{\phi}\sin\theta\sin\varphi + \hat{z}\cos\theta$

We show that the hybrid skyrmion can stabilize through the interplay between interfacial DMI and either bulk DMI or dipolar interaction. We can also control the helicity of the hybrid skyrmion by tuning the ratio of Di/Db when there is no dipolar interaction, or simply by adjusting the D_i when the D_b is absent [1]. Our results suggest that hybrid skyrmions can exist within $0 < |D_i| < 0.4$ mJ m−2 for Co-based magnetic systems.

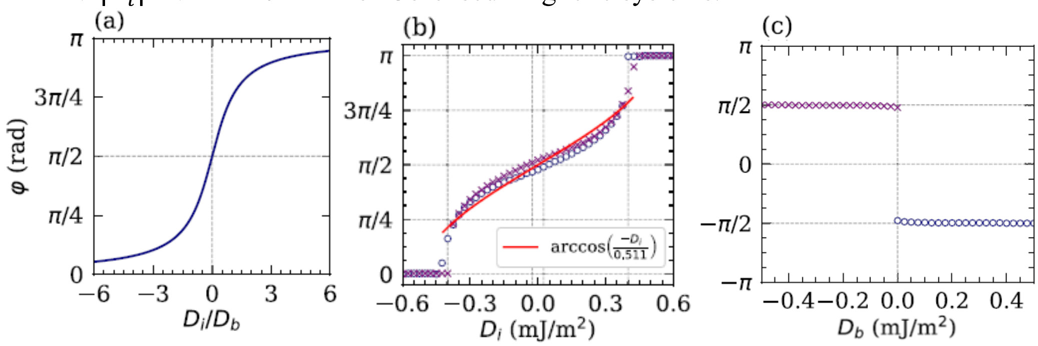

Figure 2. Hybrid skyrmion occurs under (a) zero dipolar interaction or (b) zero D_b*. (c) Zero* D_i *only produces Bloch skyrmion*

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Enhanced spin-orbit torque efficiency with a bulk WSe2 spin sink

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Spin-orbit torque (SOT) offers an efficient method to manipulate magnetic materials, holding promise for various applications. A key focus of current research is improving SOT efficiency by interface engineering. Transition metal dichalcogenides (TMDs), exhibiting strong spin-orbit coupling, can function as a spin source [1] or sink [2] in few layers. In this work, we explore the enhancement of SOT through the introduction of a bulk WSe_2 underlayer in Pt/Py/Al trilayer. Our results reveal that the WSe_2 underlayer significantly enhances both spin mixing conductance and damping-like torque efficiency using spin-torque ferromagnetic resonance (ST-FMR) measurement (illustrated in Fig. 1). The spin transparency model suggests this enhancement arises from the WSe_2 layer reducing spin backflow, which leads to improved SOT efficiency.

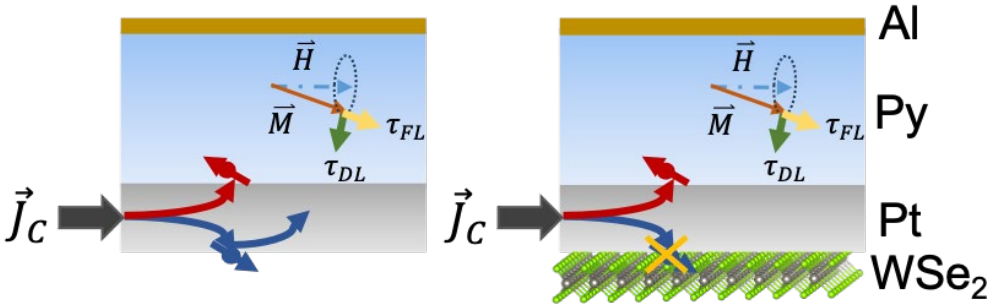

Fig. 1 In the WSe_2 (bulk)/Pt(2 nm)/Py(t nm)/Al(2 nm) multilayer, the WSe_2 layer functions as a spin sink.

Keywords: spin-orbit torque, spin backflow, ST-FMR, spin mixing conductance

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Spin-orbit torque efficiency enhancement to tungsten-based SOT-MTJs by interface modification with an ultrathin MgO

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Spin-orbital torque (SOT) based three-terminal magnetic tunnel junctions (MTJs) have attracted much interest as the next-generation magnetic random-access memory (MRAM) key device both in the academy and the industry. This is because SOT-MTJs feature high endurance and fast switching speed, benefiting tremendously from the separation of read/write current paths and less incubation time during the write in contrast to the spin-transfer torque (STT) MTJs [1]. The pursuit of high density, ultrafast writing speed, and low power consumption of SOT-MRAM devices makes researchers work on higher charge-to-spin current conversion efficiency (ξ_{DL}) of the heavy metal (HM) layer. However, previous studies showed that the highest ξ_{DL} was about -0.4 for β-W [2]. This value is lower than the typical spin polarization P ≈ 0.6 for widely used CoFeB materials in STT-MTJs [3]. So our purpose in the present study is to further improve the ξ_{DL}. To reach this, we systematically investigated how an ultrathin MgO interlayer inserted in between the W and the CoFeB affects the ξ_{DL} experimentally from the harmonic measurements as well as the switching behaviors of the fabricated SOT-MTJs and theoretically from the first-principal calculations.

As shown in Figure 1, a large ξ_{DL} (-0.58) was obtained for the W/CoFeB heterostructures by introducing a 0.22-nm-thick MgO interlayer in between. This value was 45% enhanced as compared to that without the MgO interlayer. Moreover, the switching current density (J_{SW}) was reduced by 48% tested under 1-ns-width pulses for the full W/MgO interlayer/CoFeB-based spin-orbital torque (SOT) magnetic tunnel junctions (MTJs). The J_{SW} decreases with increasing the MgO interlayer thickness till 0.22 nm under both DC and 10-ns-width pulse test consistent with the behavior of the ξ_{DL}.

The improvement of the efficiency can be theoretically explained by the enlarged interfacial Rashba effect due to the existence of the Mg-O on top of the W from the first-principal calculations. The promising results give potential solutions to the high-power dissipation issue for the tungsten-based SOT-MTJs.

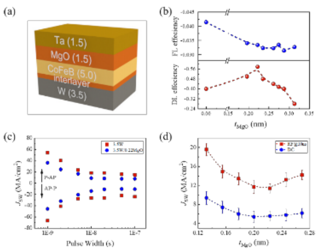

Figure 1. (a) Schematic diagram of the film stacks. (b) The subtracted damping-like torque and field-like torque efficiencies obtained from samples. (c) The extracted J_{SW} as a function of the pulse widths for both P-to-AP and AP-to-P switching directions. The red squares (blue circles) are the data for the MTJs without (with) the MgO interlayer. (d) The MgO interlayer thickness dependence of the extracted J_{SW} under the DC and 10-ns width pulse testes, respectively. The error bars are the standard deviations of the JSW measured for 10 devices.

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Spin and orbital Hall effects in V and Pt

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The conversion of electrical current into spin current has been one of the primary interests in Spintronics, scientifically as well as technologically[1]. The orbital Hall effect [2, 3], a phenomenon that converts electrical current into orbital current, has gained significant attention recently owing to its potential applications in technology. Although many experiments use the torque acting on the magnetization of a magnetic layer stacked on a non-magnetic layer to probe the orbital current from the latter [4], it is difficult to precisely assess the magnitude of the orbital current. The magneto-optical Kerr effect (MOKE) has been proven as a viable technique to probe spin and orbital accumulations in non-magnetic materials [5,6]. Here, we employ this technique to investigate the accumulation of spin and orbital magnetic moments at the metal surface due to the spin and/or orbital Hall effects in V and Pt, transition metals that possess weak and strong spin-orbit interactions.

V and Pt thin films of varying thicknesses were prepared using RF magnetron sputtering. The films were formed into Hall bars by using a metal shadow mask technique. The current-induced spin and orbital Hall currents were measured using longitudinal MOKE. The results are shown in Fig. 1. The current-induced MOKE signal increases with increasing thickness of V (up to ~100 nm). The signal is significantly larger than that of Pt, which shows a relatively weak thickness dependence. We analyzed this difference using analytical model calculations combined with first-principles calculations[6]. We discuss the origin of the current-induced MOKE signal in metallic thin films.

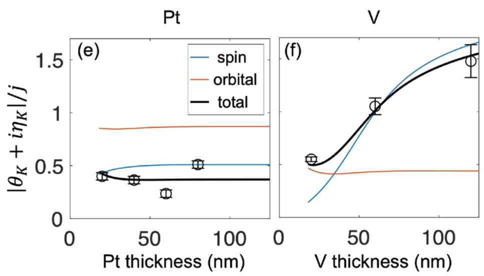

Figure 1: Current-induced MOKE of (left) Pt and (right) V with different thickness.

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Arrays of coupled magnetic tunnel junctions for mechanical applications

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The magnetic tunnel junction (MTJs) is the most promising spintronic device. A spintronic accelerometer has been proposed by exploiting a system of MTJs in which the MTJs, working as spin-toque oscillators (STOs) and spin-torque diodes (STDs), are integrated on excitable substrates such as microelectromechanical systems (MEMS) that can transduce the external stimulus (a_{ext}) into a mechanical excitation, which translates into an excitation of the magnetic system via the stray field that couples the MTJs. The change in the displacement reflects into a variation of the dipolar coupling that affects the synchronisation between the MTJ, and this results in a change in the output voltage generated by the MTJs working as STD via spin diode effect [1]. By exploiting the properties of the system, this change in the output voltage allows to extract the acceleration directly [2,3].

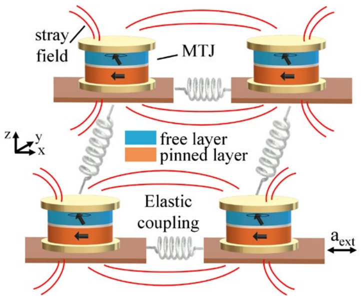

Figure 1: Sketch of the MTJs' array system studied in this work.

In this work we extend the design to an array of magnetic tunnel junctions. Arrays of MTJs provides means to improve the sensitivity and energy efficiency of the accelerometer. Moreover, this design could also be exploited in other applications, such as microwave amplifiers and reservoir computing. Here we explore different design configurations and perform systematic studies on the dynamics of the array of MTJs, both mechanical and magnetic, to find those conditions that yield a stable synchronisation between the MTJs, a linear output signal from the fixed-MTJs and allows to maximise the output sensitivity.

Acknowledgements. This work was supported under the project number 101070287 – SWAN-on-chip – HORIZON-CL4-2021-DIGITAL-EMERGING-01; the MUR-PNRR project SAMOTHRACE (ECS00000022), funded by European Union (NextGeneration EU); the projects PRIN 2020LWPKH7 – The Italian factory of micromagnetic modeling and spintronics and PRIN_20225YF2S4 – Magneto-Mechanical Accelerometers, Gyroscopes and Computing based on nanoscale magnetic tunnel junctions (MMAGYC), funded by the Italian Ministry of University and Research.

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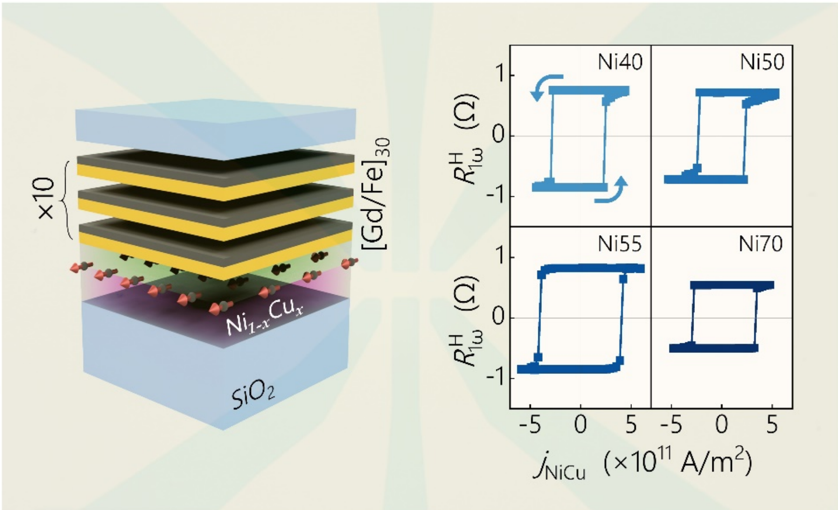
Spin–orbit torques and magnetization switching in Gd/Fe multilayers generated by current injection in NiCu alloys

F. Nasr, F. Binda, C.-H. Lambert, G. Sala, P. Noël, and P. Gambardella

Spin–orbit torques[1] (SOTs) are current-induced magnetic torques originating from the conversion of a charge current into spin-orbital accumulation in a material adjoining a magnetic layer. SOTs represent an effective and reliable tool for writing the memory cells of magnetoresistive random-access memories, driving domain wall motion, and realizing spin-torque nano-oscillators.

So far, the generation of SOTs has mostly relied on charge-to-spin conversion processes taking place in heavy metals, such as Pt and W, and topological insulators, owing to their strong spin-orbit coupling. Increasing efforts thus focus on identifying alternative SOT material systems, which are both abundant and compatible with conventional semiconductor processing.

We report measurements of SOTs generated by $Ni_{1-x}Cu_x$ alloys in perpendicularly magnetized ferrimagnetic Gd/Fe multilayers[2]. We show that the efficiency of the SOTs increases with the Ni/Cu atomic ratio, reaching values comparable to those of Pt for $Ni_{55}Cu_{45}$. Furthermore, we demonstrate magnetization switching of a 20-nm-thick Gd/Fe multilayer with a threshold current that decreases with increasing Ni concentration, similarly to the SOT efficiency. Our findings show that light metal alloys consisting of *3d* elements are efficient materials for implementing sustainable spin current generators and electrically control the magnetization in spintronic devices.



[1] A. Manchon, J. Železný, ..., and P. Gambardella, Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems, *Rev. Mod. Phys.* **91**(3), 035004 (2019).
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Spin-orbit torque driven by interfacial chemistry in topological BiSb/NiFe bilayers with Ti insertion

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[c] Formerly with Western Digital, San Jose, CA 95119, USA
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Topological insulators (TIs), particularly BiSb, have garnered significant attention in spintronics due to their unique electronic properties for large spin-orbit torque (SOT) efficiency. [1,2] However, TI thin films face challenges in low melting point, high diffusivities, low bulk conductivity, and degraded topological surface states when combined with a ferromagnetic layer, which impedes the widespread applications of TIs. In this work, BiSb thin films with a NiFe ferromagnetic layer were prepared, and the impact of Ti insertion on SOT efficiency was explored. Remarkably, a Ti spacer layer enhanced SOT efficiency, persisting after aging and annealing, offering insights into interfacial interdiffusion for improved spintronics applications.

All the thin films were grown on sapphire c-plane $Al_2O_3(0001)$ substrates by magnetron sputtering at room temperature. Structural properties were characterized by reflection high energy electron diffraction (RHEED), X-ray diffraction (XRD), atomic force microscopy (AFM), and high-angle annular dark-field scanning transmission electron microscopy (STEM). Two samples, BiSb/NiFe and BiSb/Ti/NiFe, were compared under different conditions, i.e., as-deposited, room temperature aged for 45 days, and annealed at 400 K for 1 hour. Conventional UV lithography was employed to fabricate coplanar waveguide devices to evaluate SOT efficiency through the spin-torque ferromagnetic resonance (ST-FMR) method. After deposition of BiSb, RHEED patterns revealed semi-polycrystalline growth, with improved crystallinity observed after annealing. The AFM image displayed a remarkably flat surface with an average roughness of 0.7 nm for the as-deposited 8-nm-thick BiSb thin film. Thickness-dependent resistivity measurements for the BiSb thin films illustrated the emergence of topological surface states, with increased resistivity in thicker films. XRD spectra confirmed the existence of robust 001 texture of the BiSb thin films, particularly in films thicker than 8 nm. Subsequently, ST-FMR measurements demonstrated an enhanced SOT efficiency of 1.2, achieved in the sample with a Ti spacer layer, which is around 4 times higher than in the sample without Ti interlayer layer. The enhancement of SOT efficiency could be attributed to protecting topological surface states and preventing interdiffusion due to Ti insertion. Microstructural analysis from cross-sectional STEM indicated an improved crystallinity in the Ti-inserted sample after annealing. Elemental analysis revealed the role of Ti in suppressing interdiffusion and preserving topological properties, contributing to a substantial increase in SOT efficiency.

These results provide crucial insights into the complex interfacial microstructures, emphasizing the pivotal role of the Ti spacer layer in enhancing SOT efficiency in BiSb/NiFe structures, potentially paving the path for practical applications of BiSb-based topological materials in spintronics.

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Energy-efficient SOT-MRAM writing operation using amorphous W-Ta-B as a spin Hall material

Yuki Hibino, T. Yamamot, T. Taniguchi, K. Yakushiji, H. Kubota, and S. Yuasa

National Institute of Advanced Industrial Science and Technology, Research Center for Emerging Computing Technologies, Tsukuba, Japan

Current-induced spin-orbit-torques (SOTs) enable fast and reliable magnetization switching, which can be a new data writing method for magnetoresistive random-access memories (SOT-MRAMs) [1]. Heavy metal material with a large spin Hall effect (spin Hall material) is a typical spin source of SOTs, and material choice is the most important factor for developing SOT-MRAMs [2,3]. For practical applications, spin Hall materials need to have not only high SOT efficiency but also compatibility with CoFeB/MgO-based magnetic tunnel junctions (MTJs), high thermal tolerance for the back-end-of-line process, etc. β-W is one of the candidate materials because of its large spin Hall angle [2] and compatibility with MTJs [2,3]. However, its low thermal tolerance, which originates from its metastable crystal structure, is a serious flaw of β-W [3]. To overcome this issue, previous works have focused on how to stabilize the β-phase structure, for example, by adding oxygen and nitrogen dopants [3,4].

Here, we present a new approach, which is to use amorphous spin Hall materials, to simultaneously satisfy both large SOT efficiency and high thermal tolerance. Even without a long-range crystal order in amorphous W-Ta-B alloys (Fig. 1a), the alloys exhibit a large SOT efficiency of up to 40%, which is even larger than that of the crystalline β-W. The large SOT efficiency is attributed to the intrinsic mechanism of the spin Hall effect in short-range order and the effect of Ta substitutional doping. Moreover, the thermal tolerance of W-Ta-B can reach up to 400°C because the boron atoms effectively stabilize the amorphous state. We also fabricated nanoscale three-terminal SOT-MRAM memory cells consisting of W-Ta-B spin Hall channel and MTJ. As a result, we demonstrated both high magnetoresistance ratios up to 130% and low intrinsic switching current densities down to 4×10^6 A/cm^2 (Fig. 1b) [5].

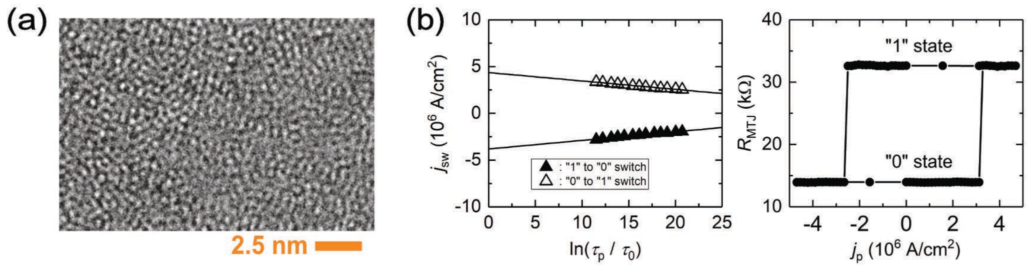

Figure 1: (a) High-resolution Transmission Electron Microscope (TEM) image of amorphous W-Ta-B alloy. (b) Pulse width dependence of the switching current density (left) and switching curve under 1 ms pulse width (right). τ_0 corresponds to the inverse of attempt frequency (τ_0 = 1 ns).

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Enhanced annealing stability in perpendicularly magnetized magnetic tunnel junctions using an Fe-substituted MgO barrier

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Magnetic tunnel junctions (MTJs) showing a large tunnel magnetoresistance (TMR) as well as a large perpendicular magnetic anisotropy (PMA) have been intensively studied to develop high speed and energy efficient spintronic devices such as magnetoresistive random access memories. To date, MgO have been most used as a tunnel barrier in practical MTJs owing to the giant TMR and the large PMA in MgO-MTJs [1, 2]. Regardless of intensive studies on MgO-MTJs, it is still challenging to achieve a high annealing stability necessary for overcoming the back-end-of-line process at a temperature above 400˚C. This technological issue is partly because of the difficulty in fabricating a uniform ultrathin ferromagnetic (FM) layer on top of the MgO barrier layer due to the poor wettability. Previous studies have shown that the insertion of a nonmagnetic layer in between the FM/MgO interface improves the uniformity of FM layer [3] in exchange for a remarkable reduction in the TMR.

In this work, we develop perpendicularly magnetized MTJs using a partially Fe-substituted MgO, i.e., an $Mg_{40}Fe_{10}O_{50}$ (MgFeO), as a barrier layer. As shown in Fig. 1, the use of MgFeO substantially improves the uniformity of CoFeB/Mo/CoFeB electrode owing to the good wettability of CoFeB on MgFeO. Detailed nanostructural analysis combined with elemental distribution mapping reveals the formation of highly (001)-oriented MgFeO in the as-deposited MTJ film, and the crystalline MgFeO layer effectively inhibits diffusion of B atoms from the CoFeB layers through the MgFeO layer during the post-annealing. As a result, the MgFeO-MTJs exhibit superior annealing stability compared with conventional MgO-MTJs, and TMR ratios of over 230% is demonstrated in MgFeO-MTJs after annealing at 400˚C, as shown in Fig. 2. Ferromagnetic resonance measurements also reveal a reduced magnetic damping as well as an enhanced PMA in the MgFeO-MTJs [4].

This work is based on results obtained from a project, JPNP16007, commissioned by the New Energy and Industrial Technology Development Organization (NEDO), Japan.

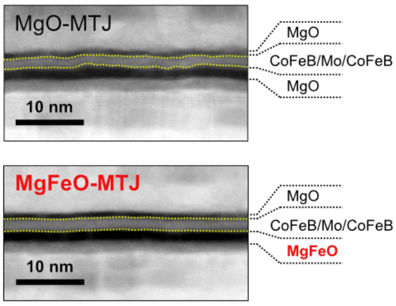

Figure 1: Scanning transmission electron microscopy images of MTJ films.

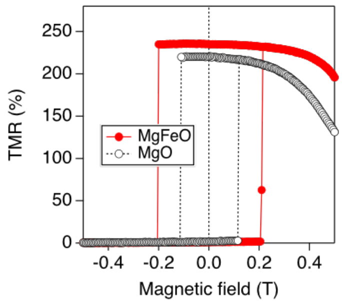

Figure 2: TMR curves of MTJ devices after annealing at 400˚C.

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Thank you!!!

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ZABRE Nanometer magnetic fields made visible.