MagnEFi CONFERENCE

OCTOBER 10-14, 2022
CRETE, GREECE

CONFERENCE PROGRAMME

Dear participants,

On behalf of our MagnEFi consortium, we are pleased to extend our warmest welcome to our conference and thank you all sincerely for your eminent support and your valuable contributions!

The MagnEFi Consortium is dedicated to work on various gating effects on spintronic devices both experimentally and theoretically with the hope of enriching the state-of-the-art spintronic paradigm and making positive impacts on our society. This project network is sponsored by the EU Commission's Marie Skłodowska-Curie Actions program (Horizon 2020). Within our network, workshops and projects meeting are regularly organized, where not only research progress within our projects are discussed, but also large span of external speakers are involved to broaden our vision on the field. As our last meeting approaches, we decided to upscale it to a conference, in which we will have the chances to be acquainted with the authorities of the field. Moreover, we would like to share our joy with more young researchers around the globe to make this conference exceptional, a dedicated conference exclusively for young researchers!

During the course of this conference, lectures ranging from substantial topics from nanomagnetism will be given by ones of the most established researchers in our field as well as other topics regarding softskill development and environmental impacts. Apart from the extensive knowledge training, we will organize a social event for not missing the crucial exotic islands experience in Crete.

We believe this gathering will give us, the young researchers, priceless opportunities to learn the advancement of the extensive field of nanomagnetism, approach the renowned researchers from the field, establish the academic networks and build up friendships among us.

We whole-heartedly hope that you will enjoy our conference as well as the time we will share with each others. We thank you once again for your participance!

Best regards,

MagnEFi ITN

MagnEFi Conference 2022

10 – 14 October 2022, Crete island, Greece

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Chiral spin textures and Josephson Diodes

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Chiral domain walls are just one member of an ever-expanding family of chiral spin textures that are of great interest from both a fundamental as well as a technological perspective [1]. Recently a zoology of complex spin textures stabilized by volume or interface Dzyaloshinskii-Moriya interactions have been discovered including, in our work, anti-skyrmions [2], elliptical Bloch skyrmions [3], two-dimensional Néel skyrmions [4] and fractional antiskyrmions [5]. Such nano-objects are potential candidates as magnetic storage bits on the racetrack [6]. Recently we have observed Néel skyrmions in two distinct but closely related 2D van der Waal's ferromagnetic compounds that should not allow for such structures. We show that the crystal structures are substantially modified by self-intercalation, lowering their symmetry and thereby allowing for chiral spin textures that require acentric structures [7, 8]. We also discuss the unusual properties of chiral Kagome antiferromagnets and how their magnetic structure can be manipulated by a previously unobserved seeded spin orbit torque mechanism [9]. Finally, we demonstrate the observation of long range triplet supercurrents in thin layers of a chiral antiferromagnet [10] and we discuss our recent finding of a nonreciprocal Josephson Diode Effect in 2D van der Waals layers [11] as well as in proximitized platinum [12].

[1] S.-H. Yang, R. Naaman, Y. Paltiel, and S. S. P. Parkin, "Chiral spintronics," *Nat. Rev. Phys.,* vol. 3, pp. 328–343, 2021

[2] A. K. Nayak *et al.*, "Magnetic antiskyrmions above room temperature in tetragonal Heusler materials," *Nature,* Letter vol. 548, pp. 561-566, 2017.

[3] J. Jena *et al.*, "Elliptical Bloch skyrmion chiral twins in an antiskyrmion system," *Nat. Commun.,* vol. 11, p. 1115, 2020.

[4] A. K. Srivastava *et al.*, "Observation of Robust Néel Skyrmions in Metallic PtMnGa," *Adv. Mater.,* vol. 32, p. 1904327, 2020.

[5] J. Jena *et al.*, "Observation of fractional spin textures in a Heusler material," *Nat. Commun.,* vol. 13, p. 2348, 2022.

[6] S. S. P. Parkin and S.-H. Yang, "Memory on the Racetrack," *Nat. Nanotechnol.,* vol. 10, pp. 195-198, 2015.

[7] A. Chakraborty *et al.*, "Magnetic skyrmions in a thickness tunable 2D ferromagnet from a defect driven Dzyaloshinskii-Moriya interaction," *Adv. Mater.,* vol. 34, p. 2108637, 2022.

[8] R. Saha *et al.*, "Observation of Néel-type skyrmions in acentric self-intercalated $Cr_{1+\delta}Te_2$," *Nat. Commun.,* vol. 13, p. 3965, 2022.

[9] B. Pal *et al.*, "Setting of the magnetic structure of chiral kagome antiferromagnets by a seeded spin-orbit torque," *Sci. Adv.,* vol. 8, p. eabo5930, 2022.

[10] K.-R. Jeon *et al.*, "Long-range supercurrents through a chiral non-collinear antiferromagnet in lateral Josephson junctions," *Nat. Mater.,* vol. 20, pp. 1358-1363, 2021.

[11] B. Pal *et al.*, "Josephson diode effect from Cooper pair momentum in a topological semimetal," *Nat. Phys.,* vol. accepted, 2022.

[12] K.-R. Jeon *et al.*, "Zero-field polarity-reversible Josephson supercurrent diodes enabled by a proximity-magnetized Pt barrier," *Nat. Mater.,* vol. online, 2022.

Surface acoustic wave driven ferromagnetic resonance

C. Gourdon[a], P. Kuszewski[a], M. Kraimia[a,b], I. S. Camara[a], A. Vythelingum[a], A. Lemaître[c], J.-Y. Duquesne[a], L. Thevenard[a]

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Magnetization dynamics may be triggered by a variety of stimuli, such as radio-frequency (rf) fields, currents, light pulses or acoustic waves. These dynamics can then be implemented in systems encoding information magnetically, such as the free layer of magnetic tunnel junctions, or the phase of spin-waves in magnonic devices. The possibility of exciting magnetization dynamics via acoustic waves arises from the coupling between strain and magnetization. This coupling, known as magnetostriction in the static regime, was long ago recognized as also efficient in the dynamical regime [1] and described as phononmagnon coupling. Acoustic waves are coherent phonons that can interact very efficiently with magnons in their typical frequency range (GHz). Surface acoustic waves (SAW), which can be excited piezoelectrically by interdigitated transducers deposited on a piezoelectric material, are particularly appropriate to study this interaction in thin magnetic layers or nanostructures on a substrate [2]. In a classical framework the SAW-driving torque on magnetization results from an effective rf magnetic field generated through the magneto-elastic energy. Its efficiency depends on the relative orientation of the acoustic wavevector and the magnetization vector.

The SAW-driven ferromagnetic resonance (FMR) will be exemplified using a thin layer of (Ga,Mn)As. Taking advantage of the magnetic anisotropy, the magnon frequency of this magnetic semiconductor can easily be tuned to typical SAW frequencies via an applied magnetic field. We will show that SAW-driven FMR is observed as the absorption of the SAW accompanied by a peak in the magnitude of the magnetization precession using acoustic wave detection technique and time-resolved magneto-optical effects [3], respectively. We will describe in detail the experimental techniques implemented, the pros and cons of this approach compared to other magneto-acoustic excitations.

We will also demonstrate how one can reach the non-linear dynamics regime using large amplitude surface acoustic waves (SAW) [4]. Signatures of the non-linear magnetoacoustic response on the magnetic dynamics appear as frequency and wavevector doubling, well accounted for by a parametric oscillator model.

Finally we will show the SAW-induced full resonant magnetic switching. We will explicit the conditions on magnetic field and SAW power to obtain these effects, and show they are equally efficient on in-plane and out-of-plane magnetized ferromagnets [5], [6].

We will conclude on how these results could be relevant to other magnetic systems, such as antiferro- or ferri-magnets.

[1] C. Kittel, Phys. Rev. **110**, 836May (1958).

[2] L. Dreher *et al.*, Phys. Rev. B **86**, 134415 (2012).

[3] P. Kuszewski *et al.*, Phys. Rev. Appl.**10**, 034036 (2018).

[4] M. Kraimia *et al.*, Phys. Rev. B, **101**, 144425 (2020).

[5] P. Kuszewski *et al.*, J. Phys. Condens. Matter, **30**, 244003 (2018)

[6] L. Thevenard *et al.*, Phys. Rev. B, **93** 134430 (2016.)

Magnetic garnets for spintronic and photonic devices

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

References: Nat. Commun. 12, 2498 (2021); Phys. Rev. Mat. 5, 094403 (2021); Science 370, 1438 (2020); Nature Commun. 11 1090 (2020); Nature Nanotech. 14 561 (2019); Optica 6, 473 (2019); ACS Photonics 5, 5010 (2018); Phys. Rev. Mater. 2, 094405 (2018); Nature Materials 16, 309–314 (2017); Adv. Electron. Mater. 3 1600376 (2017).

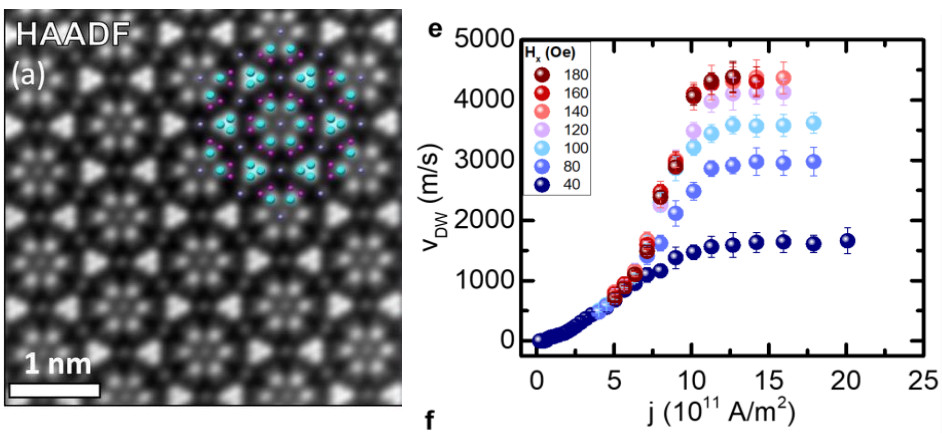

Figure 1: Left: High resolution plan view electron micrograph of a (111)-oriented terbium iron garnet film. Blue: rare earth; purple: Fe sites. Right: domain wall velocity *v* reaches 4.3 km/s in Bi-substituted yttrium iron garnet, driven by a current *j* in a Pt overlayer, for different in-plane fields.

Ultrafast magnetism – terra incognita beyond the classical approximations

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While magnetism is essentially the strongest quantum mechanical phenomenon, modern description of magnetization dynamics and magnetization reversal relies on thermodynamics and the corresponding approximations. I will show that ultrashort (sub-100 ps) stimuli push magnetic media into a strongly non-equilibrium state, where the conventional description of magnetic phenomena in terms of equilibrium thermodynamics fail and the experimentally observed ultrafast magnetization dynamics and reversal challenge the current theories. For instance, while the conventionally accepted Curie-Neumann's principle states that "the symmetries of the causes are to be found in the effects" [1], in ultrafast magnetism the principle fails and magnetization dynamics becomes counter-intuitive:

1) Although, according to thermodynamics and simply intuition, heat can only destroy magnetization, we will demonstrate that ultrafast (sub-100 ps) heat pulse can cause magnetization reversal without any magnetic fields [2].

2) While control of spins in antiferromagnets requires increasingly high magnetic fields, rapidly varying magnetic field at THz rates become a game-changer in the field. Picosecond pulses of THz magnetic field with the strength below 1 T can efficiently excite spins in antiferromagnets and even push spin dynamics into nonlinear regime [3].

Finally, we will discuss recent advances in ultrafast writing of magnetic bits. In particular, I would like to highlight that ultrafast magnetism can be the way to write information in the record fast and the least dissipative way [4].

[1] P. Curie, J. Phys. Theor. Appl., 393–415(1894) [https://en.wikipedia.org/wiki/Curie%27s_Principle]

[2] T.A. Ostler et al, *Ultrafast heating as a sufficient stimulus for magnetization reversal in a ferrimagnet*, Nature-Communications **3**, 666 (2012).

[3] E. A. Mashkovich et al, *THz light driven coupling of antiferromagnetic spins to lattice*, Science **374**, 1608-1611 (2021).

[4] A. Stupakiewicz et al, *Ultrafast nonthermal photo-magnetic recording in a transparent medium*, Nature **542**, 7639 (2017).

MRAM concepts for sub-nanosecond switching, ultimate scalability and improved thermal stability

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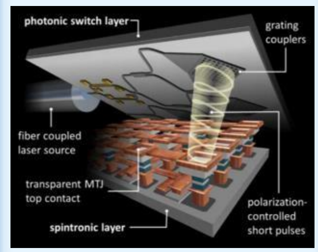
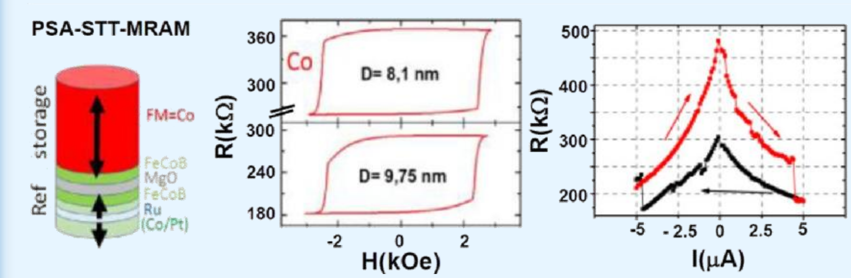
The development of magnetic-tunnel-junctions-based MRAM memories calls for technological breakthroughs intended to go well above the GHz operation speed, to match the speed of the processor. A very promising solution combines the spin-photon interaction, which enables the ultrafast reversal of the storage layer magnetization under the action of a laser pulse of few tens of fs duration. In the framework of the H2020 project called SPICE, SPINTEC demonstrated a conceptually new spintronic-photonic memory chip demonstrator (see fig. 1**)** with faster speed and lower energy consumption, as a cornerstone of a novel integration platform that combines photonic, magnetic and electronic components.



Schematic view of a hybrid spintronic-photonic demonstrator for ultrafast magnetic memories.

In conventional spin-transfer-torque (STT) magnetic random access memory (MRAM), lateral size reductions lead to limited storage retention. We proposed and validated a new MRAM cell concept using shape anisotropy suitable to achieve high retention at sub-10nm critical dimensions. In this concept, the thickness of the storage layer is significantly increased to values comparable to the cell diameter. A further advantage of perpendicular shape anisotropy is to be a robust source of bulk anisotropy less sensitive to temperature, while in conventional MRAM, the thermal sensitivity of the interfacial anisotropy is a limitation to MRAM applications requiring a wide range of operating temperatures – see fig. 2



Quasi-static measurements demonstrate the stability, as well as field- and current -induced switching by spin transfer torque for PSA stacks based on a 60 nm thick Co storage layer. The cell diameter is estimated from the electrical resistance of the tunnel junction.

Magnetosensitive e-skins and stretchable giant magnetoresistive sensors

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Conventional magnetic field sensors are fabricated on flat substrates and are rigid. Extending 2D structures into 3D space relying on the flexible electronics approaches allows to enrich conventional or to launch novel functionalities of spintronic-based devices by tailoring geometrical curvature and 3D shape. Here, we will review fundamentals of 3D curved magnetic thin films [1,2] and primarily focus on their application potential for eMobility, consumer electronics, virtual and augmented reality appliances. The technology platform relies on high-performance magnetoresistive and Hall effect sensors deposited or printed on ultrathin polymeric foils. These skin conformal flexible and printable magnetosensitive elements enable touchless interactivity with our surroundings based on the interaction with magnetic fields [3], which is relevant for electronics skins [4,5], smart wearables [6,7], soft robotics [8] and human-machine interfaces [4-7,9,10]. In this talk, recent fundamental and technological advancements on flexible magnetoelectronics will be reviewed.

[1] D. Makarov et al., “New Dimension in Magnetism and Superconductivity: 3D and Curvilinear Nanoarchitectures”, Adv. Mater. 34, 2101758 (2022).

[2] D. D. Sheka et al., “Fundamentals of Curvilinear Ferromagnetism: Statics and Dynamics of Geometrically Curved Wires and Narrow Ribbons”, Small 18, 2105219 (2022).

[3] G. S. Canon Bermudez et al., “Magnetosensitive E-Skins for Interactive Devices”, Adv. Funct. Mater. 31, 2007788 (2021).

[4] G. S. Canon Bermudez et al., “Electronic-skin compasses for geomagnetic field driven artificial magnetoreception and interactive electronics”, Nature Electronics 1, 589 (2018).

[5] M. Ha et al., “Printable and Stretchable Giant Magnetoresistive Sensors for Highly Compliant and SkinConformal Electronics”, Adv. Mater. 33, 2005521 (2021).

[6] P. Makushko et al., “Flexible Magnetoreceptor with Tunable Intrinsic Logic for On-Skin Touchless HumanMachine Interfaces”, Adv. Funct. Mater. 31, 2101089 (2021).

[7] G. S. Canon Bermudez et al., “Magnetosensitive e-skins with directional perception for augmented reality”, Science Advances 4, eaao2623 (2018).

[8] M. Ha et al., “Reconfigurable Magnetic Origami Actuators with On-Board Sensing for Guided Assembly”, Adv. Mater. 33, 2008751 (2021).

[9] J. Ge et al., “A bimodal soft electronic skin for tactile and touchless interaction in real time”, Nature Communications 10, 4405 (2019).

[10] S. Li et al., “Self-powered Stretchable Strain Sensors for Motion Monitoring and Wireless Control”, Nano Energy 92, 106754 (2022).

Recent advances in skyrmion reservoir computing

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Problems such as driving cars, object detection and language processing are simple for humans to learn but are still proving difficult for computers. One direction of solving such problems is to look at alternative models of computing using biology as an inspiration.

One example of such *neuromorphic computing* is reservoir computing. This is a machine learning paradigm that can be used for classification of spatiotemporal data. A reservoir computer consists of two main components: a reservoir and an output layer. The reservoir is a non-linear dynamical system with fading memory properties. To use a reservoir computer, an input signal is fed into it in the form of perturbations to the system. The dynamics of the reservoir then project this input into a high-dimensional space with the goal of converting a linearly inseparable dataset into a separable one, which can then be classified by performing linear regression using a single output layer.

Due to their intrinsic parallelism, there is recent interest in using physical dynamical systems like *magnetic skyrmion fabrics*. The prediction of using random magnetic structures including skyrmions as nonlinear resistive elements for low-power reservoir computing[1], has recently been experimentally realized [2].

To act as an effective reservoir, the system must have two desirable properties: nonlinearity and memory. We present measures to locally reveal both of these properties and exemplify them on magnetic skyrmion textures[3] (as displayed in figure 1). After showing the abilities of a single input skyrmion reservoir to recognize sine/square waves of latent inputs [4], we finally demonstrate the performance of a multichannel skyrmion reservoir at a canonical benchmark task of spoken-digits audio recognition [5]. We show that we can solve the task to a high model accuracy of 97% and a <1% word error rate - the highest reported accuracy for in-materio reservoir computers.

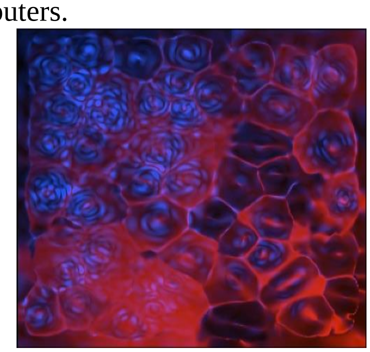

Figure 1: A gradual overlay of the non-linearity (red) and memory capacity (blue) of a magnetic skyrmion reservoir computer.

[1] D. Prychynenko, et al., Phys. Rev. Applied 9, 014034 (2018)
[2] T. Yokouchi, et al. Arxiv:2204.13260
[3] J. Love, et al., Arxiv:2108.01512
[4] D. Pinna, et al., Phys. Rev. Applied 14, 054020 (2020). [5] R. Msiska, et al., Arxiv preprint

Spintronic nanodevices for bioinspired computing

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In recent years, Artificial Intelligence (AI) has progressed to an astonishing level through the development of algorithms known as deep neural networks. Nevertheless, AI has to face a challenge: its considerable energy consumption, order of magnitudes higher than brains on similar tasks. Neuromorphic computing aims at designing systems whose operating principles are to some extent inspired by brains, to reduce the energy consumption of AI. In this tutorial, we will try to understand why brains are more energy efficient than current AI, and how spintronic devices and materials can help close this energy gap.

Looking at the organization of the brain will teach us fundamental lessons on the design of neuromorphic systems, which should closely associate computational units (artificial neurons) and memory units (artificial synapses). We will see that one of the biggest challenges, however, is the inadequacy of current memory technologies. We will then study how spin torque and other spintronic memories, which naturally resemble synapses, can by contrast provide a solution. Second, we will study recent developments that use the physics of spintronic devices, such as spin torque nanooscillators, directly for implementing artificial neurons. We will see the benefits and the challenges of this approach to computing, which mimics very closely the way that brains use their own basic devices. The specificities of spintronics, which can be tuned and engineered finely, are particularly exciting for this vision and open different perspectives in terms of scaling.

We will also see that neuromorphic systems are sometimes less demanding in terms of device properties than conventional systems, which can allow using devices in a more optimal fashion. We will study the two main applications of neuromorphic hardware (inference and learning hardware), and show that they have very different device requirements. We will finally compare two visions for neuromorphic computing: the AI approach, which can bring immediate applications, and the longer term neuroscienceinspired approach. All these approaches do not call for the same device work.

Ferrimagnetic Spintronics

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Ferrimagnet is a material having two inequivalent sublattices with different magnetic moments which are coupled antiparallelly. When the Landé g-factors of two sublattices are different, the ferrimagnet has two special temperatures below the Curie temperature, namely, the magnetization compensation temperature (T_M) where the magnetic moments of sublattices cancel each other, and the angular momentum compensation temperature (T_A) where the net angular momentum vanishes. The nature of the spin dynamics of the ferrimagnets is expected to change from ferromagnetic to antiferromagnetic as approaching T_A. Furthermore, the net magnetic moment of ferrimagnets is nonzero at T_A and can thus couple to an external magnetic field, opening a new possibility of field-driven antiferromagnetic spin dynamics [1].

We found the fast field-driven domain wall (DW) motion in ferrimagnetic GdFeCo at T_A [1]. The collective coordinate approach generalized for ferrimagnets and atomistic spin model simulations show that this remarkable enhancement of DW velocity is a consequence of antiferromagnetic spin dynamics at T_A. The antiferromagnetic spin dynamics at T_A results in another peculiar phenomenon; vanishing the skyrmion Hall effect at T_A [3]. We also examined the effect of spin-transfer torque on the motion of DW in ferrimagnets and found that the adiabatic spin transfer torque changes its sign at T_A and non-adiabatic spin transfer torque shows a peak at T_A [4]. We also found bulk Dzyaloshinskii-Moriya interaction (DMI) in amorphous GdFeCo. This bulk DMI is attributed to an asymmetric distribution of elemental content in the GdFeCo layer, where spatial inversion symmetry is broken throughout the layer [5].

This work was partly supported by JSPS KAKENHI (20H05665, 20H00337), JST CREST (Grant No. JPMJCR21C1), Collaborative Research Program of the Institute for Chemical Research, Kyoto University, and Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University.

[1] Se Kwon Kim et al., Nature Materials 21, 24 (2022).

[2] Kab-Jin Kim et al., Nature Materials 16, 1187 (2017).

[3] Yuushou Hirata et al., Nature Nanotechnology14, 232 (2019).

[4] Takaya Okuno et. el., Nature Electronics 2, 389 (2019).

[5] Duck-Ho Kim et. al., Nature Materials 18, 685 (2019).

Antiferromagnetic systems: spin dynamics and thermally excited magnons

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The ability to control the motion of magnetic structures, like domain walls (DW), is a key point in the development of many spintronic and magnetic devices. Although they have played mostly a passive role in devices so far, antiferromagnetic (AF) materials present some appealing properties that, together with the development of different techniques to manipulate and detect the orientation of their Néel vector, confer on them a major role in the future of spintronics [1].

Theoretical investigations have shown that domain walls (DWs) in AF materials can move much faster than their ferromagnetic counterparts, because their dynamics is mainly governed by the exchange interaction between magnetic sublattices [2,3]. In a similar way than in ferromagnets, current-driven DW motion in AF materials can be achieved via spin-transfer torque, field gradients, anisotropy gradients, magnonic currents [4,5], or thermal gradients [6,7]. Additionally, it was shown that besides the AF are rather insensitive to moderate external magnetic fields, they can be used to break the symmetry between the two degenerated modes of the AF spin-waves, which leads to a spin transport under the effect of a temperature gradient. Moreover, in low anisotropy AF an external applied field can be used to generate a small magnetic moment and modify the orientation of the Néel vector close to the Spin-Flop transition or enhances magnon reflection, which contributes to the thermally driven domain-wall motion [8]. From the experimental side, there is already strong evidence of thermally excited spin currents in different AF materials. Studies performed under the effect of an external magnetic field showed an increment of the spin Seebeck signal with the applied field amplitude [9]. These experimental and theoretical results lead to the question of whether an applied field influences thermally induced DW motion in AF materials.

In this talk we will discuss the different approaches used to model the magnetic response of antiferromagnetic materials, the evaluation of the ground state, and thermal stability. We will describe the main differences between AF dynamics and their ferromagnetic counterpart. Finally, we will analyze the thermally driven DW motion in a biaxial AF material, to solve the question stated above.

[1] V. Baltz et al, Rev. Mod. Phys. 90, 015005 (2018).
[2] V. G. Bar'yakhtar, B. A. Ivanov, and M. V. Chetkin, Sov. Phys. Usp. 28, 563 (1985).
[3] O. Gomonay et al, Nat. Phys. 14, 213 (2018).
[4] E. G. Tveten, A. Qaiumzadeh, and A. Brataas, Phys. Rev. Lett. 112, 147204 (2014).
[5] S. K. Kim, Y. Tserkovnyak, and O. Tchernyshyov, Phys. Rev. B 90, 104406 (2014).
[6] S. Selzer et al, Phys. Rev. Lett. 117, 107201 (2016).
[7] S. M et al, Phys. Rev. Lett. 116, 097204 (2016).
[8] P. Shen, Y. Tserkovnyak, and S. K. Kim, J. Appl. Phys. 127,223905 (2020).
[9] S. Seki, et al, Phys. Rev. Lett. 115, 266601 (2015).

Brillouin light scattering measurements of magnetic materials

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This lecture will introduce the Brillouin inelastic light scattering technique (BLS) and its application to the measurement of nearly all micromagnetic parameters of the ultrathin films (of the order of 1 nm thickness), which are the present workhorse of Spintronics. Indeed, even if BLS has witnessed a clear revival in the recent years as it a rather direct technique to measure the anti-symmetric exchange term (the Dzyaloshinskii-Moriya interaction, DMI) induced by interfaces [1], it also allows accessing other micromagnetic parameters that are difficult to measure otherwise, given the small thickness of such samples.

The basics of the technique will be introduced first (spin waves, photon-spin wave interaction) as well as some practical aspects of the spectrometer used.

A large part of the time will be allocated to discuss practical cases, including recent work on the dependence of interfacial DMI on the thickness of adjacent layers [2], as well as on the measurement of the micromagnetic parameters of intermetallic ferri-magnetic ultrathin films [3].

In closing, a comparison with the ferromagnetic resonance (FMR) will be presented, and some open questions discussed.

[1] Interfacial Dzyaloshinskii-Moriya interaction in perpendicularly magnetized Pt/Co/AlOx ultrathin films measured by Brillouin light spectroscopy; M. Belmeguenai, J.-P. Adam, Y. Roussigné, S. Eimer, T. Devolder, J.-V. Kim, S.M. Chérif, A. Stashkevich, A. Thiaville; Phys. Rev. B 91, 180405(R) (2015).

[2] Spatial extent of the Dzyaloshinskii-Moriya interaction at metallic interfaces; W. Legrand, Y. Sassi, F. Ajejas, S. Collin, L. Bocher, H. Jia, M. Hoffmann, B. Zimmermann, S. Bluegel, N. Reyren, V. Cros, A. Thiaville; Phys. Rev. Mater. 6, 024408 (2022).

[3] Quantitative analysis of spin wave dynamics in ferrimagnets across compensation points; E. Haltz, J. Sampaio, S. Krishnia, L. Berges, R. Weil, A. Mougin, A. Thiaville; Phys. Rev. B 105, 104414 (2022).

Orbital currents versus spin currents: How they interact with magnetic textures and how they are different

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The key functionality common for most spintronic devices is control of magnetic textures by an electrical current, which is mediated by the angular momentum transfer from conduction electrons to local magnetic moments [1]. Fundamentally, conduction electrons carry angular momentum in both spin and orbital parts of the wave function. As is well known, however, the orbital quenching – lifting of the orbital degeneracy by crystal field – suppresses the orbital angular momentum (OAM) *in equilibrium* [2], which may be the reason why OAM has not received the attention that it deserves in the magnetism and spintronics research.

In this talk, I will introduce a fundamentally new direction by using OAM for spintronic applications [3]. I will explain that *in nonequilibrium*, the OAM response is often more pronounced than the spin response due to coherent superposition of orbital characters induced by external perturbations [4]. This offers a new way to control magnetic moments by injecting the induced OAM [5], and the efficiency can be higher than that of conventional methods utilizing the spin. Moreover, since the generation of the OAM is independent from spin-orbit coupling, we have a broader choice of materials including light materials [4], which is a great advantage for making sustainable devices by avoiding toxic and environmentally harmful materials. I will discuss recent experiments demonstrating that current-induced torques can be large even in materials without heavy elements [6].

Despite the similarity of the orbital current and the spin current, one question still remains: How is the orbital current different from the spin current? A unique feature of the OAM is its strong interaction with the crystal potential. In later part of the talk, I show two important manifestations of the strong interaction between the OAM and the crystal potential. First, I will show that the OAM propagates much longer distance than then spin in ferromagnets due to the orbital degeneracy imposed by the crystal symmetry, which does not have an analog for the spin [7]. Second, I will show that when the crystal potential is anisotropic, the OAM polarization of the Hall current can be noncollinear in real space. Combined with the spin-orbit coupling, it results in the spin current with noncollinear polarization, which can be used to control the magnetic texture of noncollinear magnets even without an external magnetic field [8]. All these developments may be the tip of an iceberg and can potentially lead to a new paradigm of quantum transport phenomena. I will finish the talk by discussing a perspective on orbitronics research and its potential impact on other areas [3].

[1] A. Manchon *et al*. Rev. Mod. Phys. **91**, 035004 (2019).
[2] C. Kittel, *Introduction to Solid State Physics*, 8th Edition (Wiley) 2004, Chap. 11, p. 297.
[3] D. Go *et al*. Europhys. Lett. **135**, 37001 (2021) – *Invited Perspective*.
[4] D. Go *et al*. Phys. Rev. Lett. **121**, 086602 (2018); D. Jo *et al*. Phys. Rev. B **98**, 214405 (2018).
[5] D. Go and H.-W. Lee, Phys. Rev. Res. **2**, 013177 (2020).
[6] S. Ding *et al*. Phys. Rev. Lett. **125**, 177201 (2020); J. Kim *et al*. Phys. Rev. B **103**, L020407 (2021);
S. Lee *et al*. Comm. Phys. **4**. 234 (2021); D. Lee *et al*. Nat. Comm. **12**, 6710 (2021).
[7] D. Go *et al*. arXiv:2106.07928.
[8] D. Go *et al*. Phys. Rev. Lett. **129**, 097204 (2022).

Strain Mediated Heterogeneous Multiferroics – Research Opportunities & Applications

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Strain mediated multiferroics use voltage induced strains from a ferroelectric material to drive magnetization changes in a ferromagnetic material. This voltage control of magnetism approach has long range order and relatively large efficiencies without the ohmic losses present in electric current based concepts. Efforts in this area are partially motivated by the growing issues stemming from low efficiencies in traditional magnetic based microelectronic concepts contributing to the demise of Moore's law. Specifically, researchers have shown large energy efficiency improvements (>3 order of magnitude) in strain powered magnetic bit writing (multiferroic) and spin waves propagation when compared to conventional electrical current based approaches. While these research results indicate tangible benefits of strain mediated multiferroics to the microelecctronics community, obstacles remain for device insertion while new opportunities arise from the increased efficiency for magnetic control.

The purpose of this presentation is to describe both research opportunities as well as suggest potential future applications enabled by this technology. The modeling opportunities range from developing new models combining Newton, Maxwells, with Landau Lifshitz Gilbert equations at the continuum level to exploring more fundamental concepts with Density Functional Theory DFT or bridging models with Atomic Spin Dynamics/Molecular Dynamic to explore new physics. Research opportunities are also rich in the areas of discovering, fabricating and understanding small scale ferromagnetic (magnetoelastic) materials/structures when compared to the more well-funded area of ferroelectrics (piezoelectric). With continued research advances new nanoscale applications are arising that were previously stalled due to the small efficiencies.

This presentation overviews these concepts in the context of three application spaces namely, microelectronics, nanoscale magnetic motors, and electrically small communication devices. While substantial progress has been achieved over the last decade considerable opportunities exist and are required to achieve the goal of ubiquitous multiferroic nanoscale device designs as contrasted to what is readily available at the macroscale. Therefore, strain mediated multiferroic behavior, while fundamentally understood, has not yet been adequately explored by the research community considering the many opportunities available in the "micro/nano scale". As this presentation intends to illustrate, multiferroic continues to be a research area poised for significant expansion over the next decade.

The emergence research landscape of altermagnetism

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Antiferromagnetic spintronics has been one of the most active research areas of condensed matter in recent years. As we have learned how to manipulate and understand antiferromagnets actively and their emergent topology, further surprises awaited. Turning off spin-orbit coupling, a new fresh view at the family of antiferromagnetic ordered systems reveals also an emergent new class, dubbed altermagnets, with properties unique to itself and separate from ferromagnets and antiferromagnets. We report the discovery of a third distinct magnetic phase, beyond the conventional ferromagnetism and antiferromagnetism, with non-relativistic alternating spinmomentum locking, which we dub "altermagnetism". We show that this new phase is as abundant in nature as conventional ferromagnetism and antiferromagnetism, while it displays properties unparalleled in the two traditional magnetic phases, such as spin splitting by electric crystal field. Remarkably, altermagnetism was missed over the past century of quantum-magnetism research because it cannot be identified by the conventional crystallographic and relativistic magnetic symmetries, established since the early works of Bethe, Landau, Shubnikov and others. This altermagnetic phase emerges naturally when utilizing the spin-symmetry formalism, where spin and real space are decoupled.

Spin-orbit torques in ferromagnets and antiferromagnets

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The ever-increasing demand of information technology for power-efficient components has led to the search for alternative solutions to mainstream microelectronics. In this context, spintronics devices stand out as competitive candidates, especially for memory and logic applications. A promising route harvests unconventional transport properties arising from spin-orbit coupling in magnetic heterostructures lacking inversion symmetry.

In these systems, typically multilayers of transition-metal ferromagnets and heavy materials (e.g., W, Pt, Ta, Bi_2Se_3, WTe_2), interfacial spin-orbit coupling promotes a wealth of remarkable physical phenomena: the generation of spin-orbit torques, the interconversion between spin and charge currents, and the stabilization of topological magnetic skyrmions. These effects have gathered extraordinary interest and have led to remarkable experimental breakthroughs, including extremely fast magnetic reversal, terahertz emission, and current-driven skyrmion motion. The recent synthesis of novel classes of materials, including all-oxide heterostructures, collinear and noncollinear antiferromagnets, and van der Waals heterostructures, has profoundly enriched this vivid field of research by unlocking unforeseen forms of torques and magnetic interactions, thereby enhancing the functionalities of spin-orbitronic devices.

This lecture will provide a general presentation of spin-orbit torques in magnetic heterostructures. I will first introduce key concepts in spintronics, such as spin currents and spin-transfer torque, and show how spin-orbit coupling enables new physical effects of high interest for potential applications. I will present standard phenomenological descriptions of spin-orbit torque, determine the symmetry rules that govern it, and give a broad overview of the current state-of-the-art of the field from experimental and theoretical standpoints. Finally, I will explore how spin-orbitronics takes a completely new form in materials possessing low crystalline symmetries, such as Fe_3GeTe_2, CuPt/CoPt bilayers, and noncollinear antiferromagnets (e.g., Mn_3Sn).

I hope this seminar will not only encourage electrical engineers to engage in this beguiling field of research and explore the device implications of this new technology, but also reach out to scientists working in adjacent fields (terahertz science, for instance) who could bring inspiring new ideas to spintronics [1]-[5].

[1] A. Manchon, S. Zhang, "Theory of nonequilibrium intrinsic spin torque in a single nanomagnet", Phys. Rev. B vol. 78, 212405, December 2008.

[2] J. Železný, H. Gao, K. Výborný, J. Zemen, J. Mašek, Aurélien Manchon, J. Wunderlich, Jairo Sinova, and T. Jungwirth, "2elativistic Néel-Order Fields Induced by Electrical Current in Antiferromagnets", Phys. Rev. Lett., vol. 113, 157201, October 2014.

[3] A. Manchon, J. Železný, I. M. Miron, T. Jungwirth, J. Sinova, A. Thiaville, K. Garello, and P. Gambardella, "Currentinduced spin-orbit torques in ferromagnetic and antiferromagnetic systems," Rev. Mod. Phys., vol. 91, 035004, September 2019.

[4] Guilhem Manchon, Sumit Ghosh, Cyrille Barreteau, and Aurélien Manchon, "Semirealistic tight-binding model for spinorbit torques", Phys. Rev. B vol. 101, 174423, May 2020. [5] L. Liu et al., "Symmetry-dependent field-free switching of perpendicular magnetization," Nat. Nanotech., vol. 16, pp. 277- 282, January 2021.

Digitisation and Sustainability

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The purpose of the presentation is to discuss how digital information solutions can be used to promote sustainability, climatic research and public engagement with environmental issues. In the brief introduction, the terms of 'climate change' and 'digitisation' will be discussed to provide a basis for the remainder of the presentation.

The body of the discussion will discuss the benefits of digitisation along four broad categories: research, organisation, engagement and transparency.

Research: the role of digital technologies in climatic and sustainability research will be discussed, this includes the use of internet enabled sensors, AI, image recognition, satellite photography, digital twins and others. Examples of each will be presented, for example the use of AI in developing plastic eating enzymes, wireless sensors for detecting forest fires and image recognition for wildlife monitoring.

Organisation: digital technologies can also provide powerful organisation tools for companies and institutions. New digital platforms can allow companies and NGOs to better track supply chains, increase efficiency and connect with new markets. The role of digital technology in developing decentralised green electricity mini-grids will also be discussed, including the use of so-called virtual power plants. Other examples include Internet of Things (IoT) enabled products and building management software.

Engagement: digital technologies also allow individuals and entire communities to better connect with each other, the state and companies. One interesting area for research is 'citizen science', whereby normal lay people are deputised into scientific research. Another is 'Civic Tech', online tools designed to allow citizens to become involved in important local or national issues. Another area is incentivisation apps, which engage people via providing 'gamification' or other rewards for environmentally positive behaviour.

Transparency: Digital tools can also allow consumers to be better informed about products and their sustainability. Applications such as Fairify and ASKReach can provide ethical ratings for major brands and items, while digital platforms can also be used to connect with whistleblowers. Blockchain can also play a role by creating a central ledger of transactions. All of this may allow traditional consumers to become more informed, and ultimately affect buying behaviours and producers themselves.

Downsides: Digitisation does also come with downsides which are essential to discuss. As more services move online, the energy footprint of digitisation increases. This results in more carbon and environmental damage. There are also social issues with the so-called 'Digital Divide', unemployment, privacy and conflict minerals. All these will be briefly discussed and potential solutions offered.

Topologically protected unidirectional magntoelectric switching in a multiferroic

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Electric control of magnetism and magnetic control of ferroelectricity can improve energy efficiency of magnetic memory and data processing devices. However, the necessary magnetoelectric switching is hard to achieve, and requires more than just a coupling between spin and charge degrees of freedom. We show [1] that an application and subsequent removal of a magnetic field reverses the electric polarization of the multiferroic $GdMn_2O_5$, thus requiring two cycles to bring the system back to the original configuration. During this unusual hysteresis loop, four states with different magnetic configurations are visited by the system, with one half of all spins undergoing unidirectional full-circle rotation in increments of $\sim 90^o$. Therefore, $GdMn_2O_5$ acts as a magnetic crankshaft converting the back-and-forth variations of the magnetic field into a circular spin motion. This peculiar four-state magnetoelectric switching emerges as a topologically protected boundary between different two-state switching regimes. Our findings establish a paradigm of topologically protected switching phenomena in ferroic materials.

[1] L. Ponet, S. Artyukhin, Th. Kain et al., Nature **607**, 81–85 (2022).

Incommensurate antiferromangetic order in 2D insulator $CrPSe_3$

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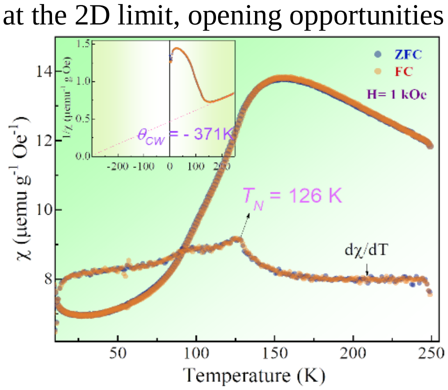
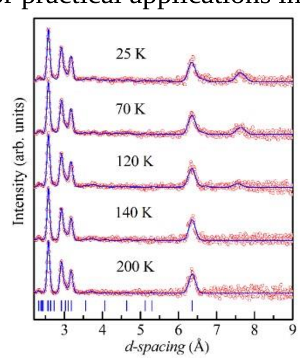
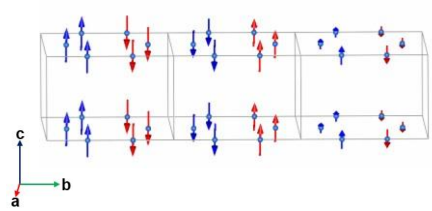
Two-dimensional van der Waals materials are an emerging class of materials because their properties including magnetic properties can be easily tuned by external forces such as gating, strain, and proximity effects. Metal phosphorus trichalcongenides (MPX_3) reveal the antiferromagnetic order even at one-layer limit. Their magnetic order can be zigzag or Neel or stripy type in hexagonal lattice with Ising and Heisenberg magnetic exchange couplings. Here we report the antiferromagnetic order in $CrPSe_3$ with spin density wave structure via neutron diffraction and magnetic susceptibility measurements. The growth temperature for crystal structure is optimized at 700 °C to avoid any secondary phases such as Cr_2Se_3 structure. The antiferromagnetic transition is revealed at T_N ~ 126 K in the magnetic susceptibility curves, which is consistent with the appearance of new peaks in neutron diffraction. A detailed analysis of neutron diffraction implies the incommensurate antiferromagnetic order in $CrPSe_3$. Our first report on the incommensurate antiferromagnetic order in 2D magnetic materials will enrich the physics of magnetism at the 2D limit, opening opportunities for practical applications in spintronics.



Susceptibility dependence on temperature



Neutron diffraction spectra



Zigzag-antiferromagnetic order with incommensurate spin distribution

Figure 1: Magnetic properties of $CrPSe_3$, (left) ZFC and FC curves reveals antiferromagnetic order with T_N~ 126 K extracted from susceptibility derivative, and high Curie-Weiss temperature from inverse susceptibility from the inset suggests presence of strong exchange couplings, (middle) Peak evolution below T_N confirms the order formation and detailed analysis of neutron diffraction data shows (right) the incommensurate zigzag type of spin order.

Brownian reservoir computing realized using geometrically confined skyrmions

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Reservoir computing (RC) has been considered as one of the key computational principles beyond von-Neumann computing. Magnetic skyrmions, topological particle-like spin textures in magnetic thin films, are particularly promising for implementing RC [1] since they respond strongly nonlinear to external stimuli and feature inherent multiscale dynamics. We propose and demonstrate experimentally a conceptually new approach to skyrmion RC that exploits the thermally activated diffusive motion of skyrmions [2]. By confining the thermal and low-energy, electrically gated skyrmion motion, together with employing spatially resolved input and readout, we find that already a single skyrmion in a confined, triangular geometry (Fig. 1) suffices to realize non-linearly separable functions, which we demonstrate for the XOR gate along with all other Boolean logic gate operations [3]. Our proposed concept can be readily extended by linking multiple confined geometries and/or by including more skyrmions in the reservoir, suggesting high potential for scalable and low-energy reservoir computing.

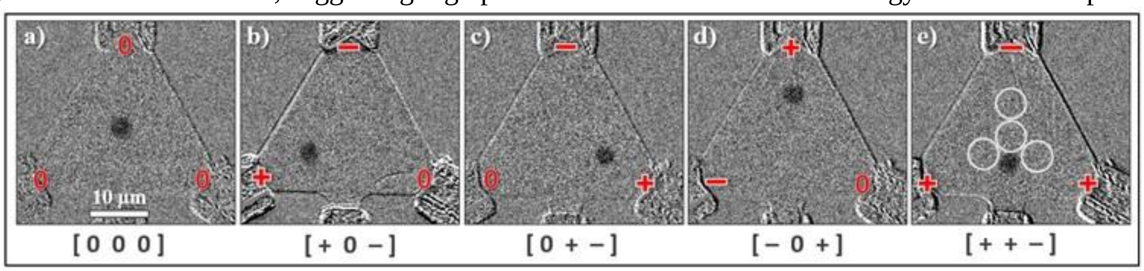

Figure 1: Skyrmion displacement. Kerr microscopy images of an equilateral triangular device, each with a single skyrmion (dark grey) in a) the ground state without and b)-
e) with applied electrical potentials. In brackets below the input patterns of the respective state. e) shows exemplary the four regions used to mimic MTJs in our analysis.

[1] D. Prychynenko, M. Sitte, *et al.*, *Phys. Rev. Applied*, vol. 9, 1 2018.

[2] J. Z´azvorka, F. Jakobs, *et al.*, *Nature Nanotechnology*, vol. 14, no. 7, 2019.

[3] K. Raab, M. A. Brems, *et al.*, arXiv:2203.14720, 2022.

Spintronic THz emitter based on Co/WS2 structure

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Terahertz wavelengths have already found numerous implementations in biology, medicine and non-destructive material analysis [1–4]. An ability to control THz polarization can be offered by spintronic emitters [5]. Recently it was showed [6], that usage of additional layer of atomically thin semiconductor in spintronic emitter results in increaseне of THz generation efficiency. Atomically thin semiconductor has role of the filter: only electrons with high excitation energy can bypass semiconductor bandgap, which supposed to lead to highly spin-polarized current.

Here we present our research on spintronic emitter based on Co/atomically thin WS2. Such chose of semiconductor driven by higher spin-orbital interaction provided by W in comparison with similar monolayers with Mo [7].THz time domain spectroscopy technique was performed to acquire THz signal from described emitter. Ultrafast demagnetization is assumed to be one of the main mechanisms of THz emission in such type of structure. Analysis of experimental results was done utilizing two-temperature model. Demagnetization times as a function of laser power were obtained.

As a result, it was shown that polarization of THz radiation from such emitter can be controlled by simple adjusting of external magnetic field. It appears to be that two different mechanisms work depending on laser power.

The work is supported by the Ministry of Science and Education of RF (Project No.075-15-2022- 1131) and Russian Science Foundation No.20-79-10223.

[1] C. Yan, B. Yang, Z. Yu, Anal. Lett. 46 (2013) 946–958.

[2] T. Notake, T. Iyoda, T. Arikawa, K. Tanaka, C. Otani, H. Minamide, Sci. Rep. 11 (2021).

[3] M. Di Fabrizio, A. D’Arco, S. Mou, L. Palumbo, M. Petrarca, S. Lupi, Appl. Sci. 11 (2021) 1–13.

[4] A.A.M. Bulbul, H. Rahaman, S. Biswas, M.B. Hossain, A. Al Nahid, Sens. Bio-Sensing Res. 30 (2020).

[5] D. Khusyainov, S. Ovcharenko, M. Gaponov, A. Buryakov, A. Klimov, N. Tiercelin, P. Pernod, V. Nozdrin, E. Mishina, A. Sigov, V. Preobrazhensky, Sci. Rep. 11 (2021).

[6] L. Cheng, X. Wang, W. Yang, J. Chai, M. Yang, M. Chen, Y. Wu, X. Chen, D. Chi, K.E.J. Goh, J.X. Zhu, H. Sun, S. Wang, J.C.W. Song, M. Battiato, H. Yang, E.E.M. Chia, Nat. Phys. 15 (2019) 347–351.

[7] D.W. Latzke, W. Zhang, A. Suslu, T.R. Chang, H. Lin, H.T. Jeng, S. Tongay, J. Wu, A. Bansil, A. Lanzara, Phys. Rev. B - Condens. Matter Mater. Phys. 91 (2015).

Influence of dusting layers on the magneto-ionic response of $Ta/Y/CoFeB/X/MgO/HfO_2$ thin film stacks

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The discovery of perpendicular magnetic anisotropy (PMA) in CoFeB/MgO magnetic tunnel junctions has paved a path in the direction of realizing high density, non-volatile spintronic devices with low power consumption. In this system, PMA is linked to the interfacial hybridization of Co-O and Fe-O, while interfaces with heavy metal elements are of great importance for the observation of Dzyaloshinskii-Moriya interaction (DMI) and spin-orbit torques. This facilitates a broad playground for voltage-driven interface engineering to modulate magnetism.

Here, we present the room temperature magneto-ionic control of magnetic anisotropy, coercivity (H_C) and Dzyaloshinskii-Moriya interaction (DMI) in

Ta/**Y**/$Co_{40}Fe_{40}B_{20}$/**X**/MgO/HfO_2, where **X** and **Y** are dusting layers of heavy metal elements (Pt,W) sharing different interfaces with CoFeB. We observe a large dependence of the magneto-ionic response on the nature and position of the dusting layers. Dusting layers at the bottom interface (**Y**) can define a system locked in a PMA state allowing for a reversible magneto-ionic control of H_C, while samples with dusting layers at the top interface (**X**) can allow for a full and reversible spin-reorientation transition. Samples with both **X** and **Y** dusting layers often present a reduced magneto-ionic response.

The intercalation of dusting layers of heavy metal elements in Ta/CoFeB/MgO stacks has the potential not only to fine tune magnetic properties and enhance magneto-ionic effects but also to individually address the contributions from each interface to the magnet-ionic mechanisms. These results are therefore of interest in terms of the understanding of magneto-ionic mechanisms and for the design of multifunctional spintronics devices.

Perpendicular magnetic anisotropy in bismuth-doped yttrium iron garnet thin films

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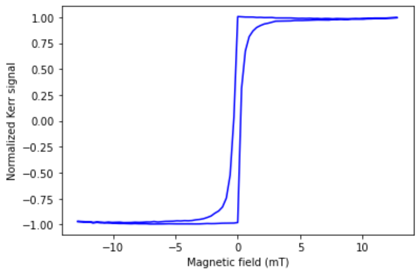
Magnetic garnet thin films exhibiting perpendicular magnetic anisotropy (PMA) and ultra-low damping have been recently explored for applications in magnonics and spintronics [1][2]. The material system offers the potential of realizing spintronic devices combining magnons and chiral magnetic textures like magnetic skyrmions, chiral domain walls, and magnetic bubbles, with applications in energy-efficient technologies.

Here we present a systematic study of PMA and magnetic damping in bismuth-doped yttrium iron garnet (Bi-YIG) thin films grown on substituted GGG (sGGG) (111) substrates. The films are grown by pulsed laser deposition (PLD), using KrF laser (λ = 248 nm), with film thicknesses ranging from 5 nm to160 nm. X-ray diffraction (XRD) measurements confirm the crystallinity of the films following post-deposition annealing at 700 °C. The surface roughness of the films, measured by atomic force microscopy (AFM), gradually increases with film thickness, from 0.3 nm for the 5 nm film to 2.2 nm for the 160 nm film. All films exhibit PMA which originates from lattice-mismatch-induced strain [2]. Hysteresis loops recorded using magneto-optic Kerr effect microscopy show square hysteresis curves for films with thickness from 5 nm to 20 nm and more rounded hysteresis curves for films with thickness from 40 nm to 160 nm, with stripe domain formation occurring at small magnetic fields. The hysteresis loop and demagnetized domain pattern of the 40 nm film are shown in Fig. 1. The dynamic magnetic properties were studied using ferromagnetic resonance (FMR) measurements with vector network analyzer (VNA) in flip-chip geometry. We observe that the damping parameter varies from ~10^{-2} to ~10^{-3} as the film thickness increases and the inhomogeneous linewidth broadening is of the order of 100 MHz.



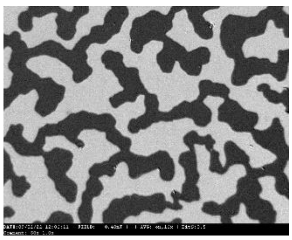


Figure 1 (a)Hysteresis loop from polar MOKE microscopy and (b) magnetic stripe domain imaged using MOKE microscopy for a film of thickness 40 nm

[1] Sheng, L. *et.al.*, Appl. Phys. Lett. 117, 232407 (2020)

[2] Soumah, L. *et.al.*, Nat. Commun. 9, 3355 (2018)

Picosecond optospintronic tunnel junctions for non-volatile photonic memories

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Perpendicular magnetic tunnel junctions (p-MTJs) are one of the building blocks for spintronic memories, which allow fast nonvolatile data access, offering substantial potential for next-generation nonvolatile memory applications[2-3]. However, the performance of such devices is fundamentally hindered by spin-polarized-current-based schemes[2-4], with a nanosecond-spin-precession-time limitation and excessive power dissipation. How to overcome these physical constraints have remained a long-lasting scientific challenge for the modern spintronics community[3,4].

To address these issues, here, we report an optospintronic tunnel junction (OTJ) device using a photonic-spintronic combination. By integrating an all-optically-switchable Co/Gd bilayer[5] with a CoFeB/MgO-based p-MTJ, an all-optical "writing" of the OTJ within 10 ps is experimentally demonstrated. It also shows a reliable electrical "read-out" with a relatively high TMR of 34%, as well as promising scaling towards the nanoscale with a low energy consumption.

Our proof-of-concept demonstration might pave the way towards a new category of nonvolatile integrated photonic memory devices. This development is considered highly promising towards next-generation ultrafast (picosecond) opto-MRAM technology thus further stimulating the innovation of future & emerging technologies.

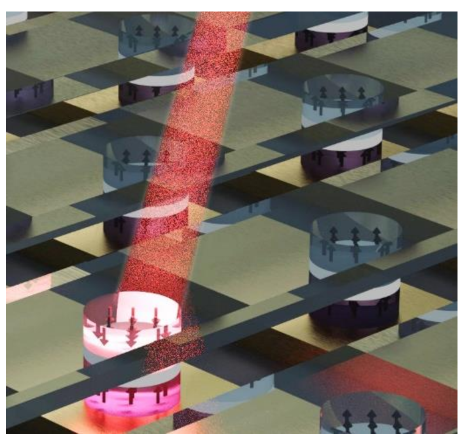

Figure 1: Artistic illustration of the optospintronic tunnel junction device

[1] Luding Wang, Houyi Cheng, Pingzhi Li, *et al.*, Picosecond optospintronic tunnel junctions, PNAS, **119** (24) e2204732119, 10.1073/pnas.2204732119.

Ultrafast emergence of ferromagnetism in antiferromagnetic FeRh in high magnetic fields

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The future of magnetic data storage crucially depends on our understanding of the mechanisms and fundamental limits on the speed of angular momentum transfer between lattice and spins. In the case of antiferromagnetic FeRh, this is a particularly interesting problem. Upon a temperature increase, the spins of Fe in FeRh suck angular momentum from the lattice - the medium becomes ferromagnetic, while the lattice expands [1].

Aiming to reveal the mechanism and the fastest possible time-scale of the magneto-structural phase transition resulted in a spin-and-lattice causality dilemma also known as a chicken-and-egg problem we carried out a time-resolved optical measurement in extreme conditions [2].

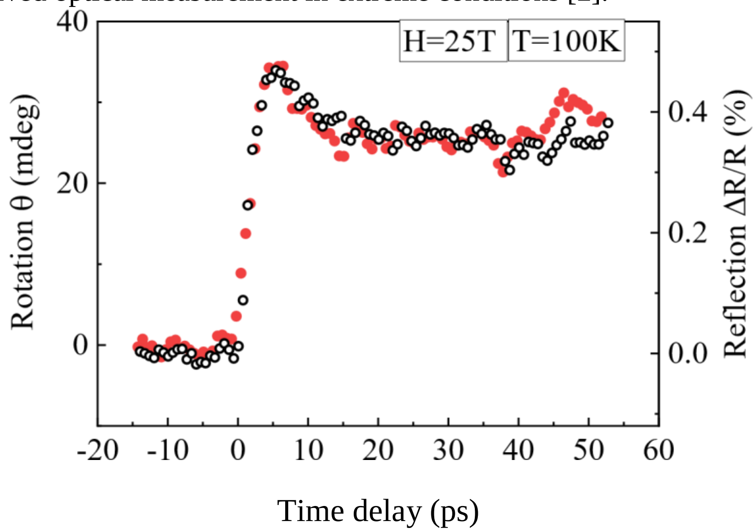

Figure 1: The polarization rotation induced by the magneto-optical Kerr effect (red) and reflectivity change (black) at 100 K and magnetic field of 25 T.

[1] L. H. Lewis, C. H. Marrows, & S. Langridge. J. of Phys. D: Appl. Phys. 49 (2016), 323002.

[2] I. A. Dolgikh, T. G. H. Blank, G. Li, et al. Prepr. arXiv:2202.03931 (2022).

Absence of Walker breakdown in the dynamics of chiral Neeldomain walls driven by in-plane strain gradients

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Magnetic domain wall (DW) motion in perpendicularly magnetized media has been a topic of intensive investigation in the last decade [1]. The conventional manner to drive a DW relies on applying an external magnetic field. Under small fields DW moves rigidly with increasing velocity up to the Walker breakdown limit, where the DW depicts precessional motion and its mobility is significantly reduced [2]. Alternative ways to drive DWs without Joule heating effects nor Walker breakdown need to be explored for novel and efficient DW-based schemes.

Here we investigate the motion of chiral Neel DWs driven by in-plane strain gradients using both micromagnetic simulations and a one-dimensional model [2,3]. The strain gradient creates a force that drives the DW towards region of higher tensile (compressive) strain for materials with positive (negative) magnetostriction. Due to the dependence of DW internal energy on in-plane strain, a damping torque proportional to the local strain arises during motion that opposes the precessional torque due to the driving force, which is proportional to the strain gradient. This prevents the onset of turbulent DW dynamics, and steady DW motion with constant velocity is asymptotically reached for any arbitrarily large strain gradient. In the transient, both the internal DW angle and the velocity change non-monotonically reaching their maximum values asynchronously. Despite complex dynamics, averaged DW velocities in the range of 500 m/s can be obtained using voltage-induced strain in piezoelectric/ferromagnetic devices under realistic conditions.

[1] E. Martinez, S. Emori and G. S.D. Beach, App. Phys. Lett. 103, 072406 (2013).

[2] N. L. Schryer and L. R.Walker, J. App. Phys. 45, 5406 (1974).

[3] A.Vansteenkiste, J.Leliaert, M.Dvornik, H. Mathias and F. Garcia-Sanchez, and B. Van Waeyenberge, AIP. adv 4, 107133 (2014).

Magnetoelectric effects in perovskite – based multiferroicsitle

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Multiferroic (MF), multifunctional materials, attract enormous research activity due to the prospects of their implementation in science in technology. Despite the variety of currently known magnetoelectric materials, perovskite – like structures remain the most researched MFs compounds. The family of perovskites stands out for its diversity due to intrinsic instability of the cubic parent perovskite phase [1].

We perform the symmetry analysis of perovskite-based multiferroics: bismuth ferrite (BiFeO3) - like, orthochromites (RCrO3), and Ruddlesden – Popper perovskites (Ca3Mn2O7 - like) explore the effect of crystallographic distortions on magnetoelectric properties. We determine the principal order parameters for each of the considered structures and obtain their invariant combinations consistent with the particular symmetry. For example, we showed that in the rare – earth orthochromites $RCrO_3$ the displacements of oxygen ions from their positions in the initial perovskite phase results in the emergence of electric dipole moments in the vicinity of the Cr ions, which are coupled with the magnetic moments of the Cr ions (Figure 1). The distortive, ferroelectric and magnetic order parameters have been classified according to irreducible representations of the D_{4h}^{16} symmetry group of $RCrO_3$, which allows to compose invariant combinations between these parameters. Symmetry consideration was implemented to the analysis of the BixR1-xFeO3 family and the Ruddlesden – Popper structures.

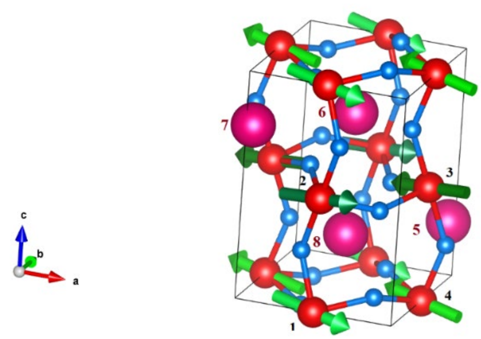

Figure 1. Electric dipole moments arrangement in RCrO3 unit cell. Green arrows denote the orientation of electric dipole moments in the vicinity of Cr3+ ions.

This research allowed us to compare the magnetoelectric effects for different crystal systems of perovskites and thus design a more meaningful organization of the desired experiments.

We acknowledge Russian Foundation for Basic Research under grant No. 19-52-80024 for support of the research.

[1] R. M. Dubrovin et al. Phys. Rev. B, vol.101, p. 180403, 2020.

Magnetic field-driven anisotropy of the second harmonic generation intensity in organic magnetoelectrics

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Magnetoelectric materials are multifunctional and have a wide range of potential applications [1]. The main requirement for magnetoelectrics is the presence of strong magnetoelectric coupling. Traditional approaches to the creation of single-phase magnetoelectrics are based on the use of inorganic materials based on oxides or fluorides [1]. Among inorganic magnetoelectrics, there are only a few examples with strong magnetoelectric coupling at room temperature [1]. In comparison with them, organic materials have great advantages: flexibility, optical transparency, low cost, environmentally friendly, and simple manufacturing processing technologies. There are some works where organic ferroelectrics are considered an alternative to traditional metal oxides [2]. The method of optical second harmonic generation (SHG) is used to study multiferroics and magnetoelectrics due to the SHG magnetic and ferroelectric tensor components are sensitive to order changes. In Ref [3] the presence of strong magnetoelectric coupling at room temperature in an organic magnetoelectric complex based on the ZnYb compound was demonstrated for the first time.

In this work, the anisotropic dependences of SHG were studied by the method of nonlinear optical microscopy. The sensitivity of the ZnYb and NiEr molecular complexes under study, and their order parameters to an external magnetic field were measured. For the ZnYb molecular complex, a change in the nature of the azimuthal dependences under the action of a magnetic field was found. A similar effect can be associated with the displacement of molecular blocks by an external magnetic field at the sites of the crystal lattice of the sample. Magnetoelectric interaction in crystals NiEr was not confirmed by the SHG method.

The work is supported by the Ministry of Science and Education of RF (Project No.075-15-2022- 1131) and Russian Science Foundation No.20-79-10223

[1] Mandal P. et al. Designing switchable polarization and magnetization at room temperature in an oxide //Nature. – 2015. – Т. 525. – №. 7569. – С. 363-366.

[2] Hang T. et al. Metal–organic complex ferroelectrics //Chemical Society Reviews. – 2011. – Т. 40. – №. 7. – С. 3577-3598.

[3] Long J. et al. Room temperature magnetoelectric coupling in a molecular ferroelectric ytterbium (III) complex //Science. – 2020. – Т. 367. – №. 6478. – С. 671-676.

Electric-Field Gating of Magnetic Multilayers with Structure Inversion Asymmetry

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Magnetic-field free stabilisation of skyrmions are a significant challenge to the design of a skyrmion based device [1]. Thus, to develop a durable and robust technology, it is required to investigate the E-field-control of the properties of skyrmions, i.e., dimension, motion, and pinning. This experimental study investigates the fundamental material properties, i.e., Dzyaloshinskii-Moriya interaction (D) and anisotropy constant (K). We are developing a material system based on Ta/Pt/CoB/Ir/Pt to which to apply E-field through a gating structure. The total thickness of the system is around 5 nm. Thus, ultrathin nonmagnetic layers reduce the effect of screening currents while ensuring that the material system has low magnetic pinning that would otherwise prevent skyrmions from being mobile [1-2].

1. Finizio, S., et al., *Deterministic Field-Free Skyrmion Nucleation at a Nanoengineered Injector Device.* Nano Letters, 2019. **19**(10): p. 7246-7255.
2. Schott, M., et al., *The Skyrmion Switch: Turning Magnetic Skyrmion Bubbles on and off with an Electric Field.* Nano Letters, 2017. **17**(5): p. 3006-3012.

Quenching extrinsic edge pinning with light ion irradiation

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Spintronic devices based on domain wall (DW) motion offer exciting new opportunities for non-volatile data storage, neuromorphic, and logic applications. However, extrinsic edge defects induced by standard nanofabrication processes can introduce DW edge pinning [1], significantly reducing the efficiency of DW motion-based devices. Edge pinning causes the DW in the wire to slow down at the edges, increasing its tensile energy, reducing its velocity and increasing its random behavior [2].

In this work, we address this problem by irradiating the edges of W-CoFeB-MgO micro-wires, with widths between 5 µm and 40 µm, using a He^+ ion beam. He^+ irradiation is a powerful tool to engineer magnetic materials at the atomic scale enabling the precise control of magnetic properties [3] and the disorder of our material [4]. We show that the edge pinning can be tuned or even quenched depending on the irradiation fluence, resulting in a significant increase in the DW velocity in the narrower wires. We also show that a similar effect can be obtained by magnetic planar patterning.

Fig. 1 shows two images of a DW moving through a 40-µm-wide wire. In Fig.1a, the edges are untreated and the DW has a positive curvature, *i.e.* the DW is slowed down by edge disorder. In Fig.1b, the edges are irradiated within the green rectangles. Before entering the irradiation zone, the DW still has positive curvature, but in the irradiated zone the curvature has become flat. This release in the tensile strength indicates a significant reduction in edge pinning due to local He^+ irradiation.

Our results show that He^+ irradiation is a versatile tool, not only to post-process magnetic properties in materials but also to reduce extrinsic pinning due to a nanofabrication process.

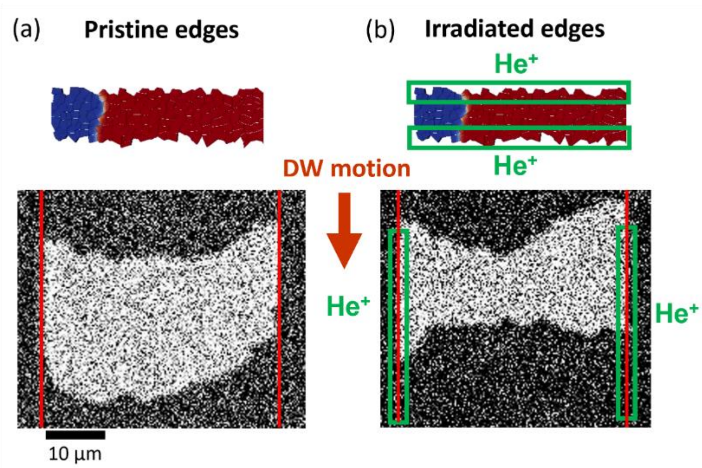

Figure 1: Differential Kerr microscopy images of a DW traveling through (a) a pristine wire, and (b) a wire with irradiated edges. The red vertical lines indicate the wire. The green rectangles denote the area irradiated with He^+ ions.

[1] Herrera Diez et al., *Phys. Rev. B* **98**, 054417 (2018)
[2] Herrera Diez et al., *Appl. Phys. Lett.* **117**, 062406 (2020)
[3] Fassbender et al., *J. Appl. Phys.* **37**, R179 (2004)
[4] van der Jagt et al., *arXiv:2208.09280* (2022)

Helium Ion Microscopy for Deterministic Multi-level SOT switching

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Spin-Orbit Torque (SOT) induced multilevel magnetization switching shows potential applications in the field of high-density data storage and neuromorphic computing. However, the difficulty to locally pattern magnetic bits with a well-defined set of several different controlled SOT switching current values limits the practical applicability of this technology.

We investigate the current induced switching properties of Pt/Co/W heterostructures with perpendicular magnetic anisotropy (PMA) by patterning into Hall bars and performing focused He^+ beam-assisted mask-less irradiation. The critical current required to switch the magnetic state depends on the saturation magnetization and magnetic anisotropy, which are interface dependent and can be tuned by the He^+ irradiation dose [1]. We do the *in-situ* monitoring of the Hall voltage under ion irradiation of different exposed areas (Fig. 1a), which not only allow us to determine the critical dose but also confirms the Hall bar's spatial sensitivity towards partial junction irradiation. By irradiating the Hall cross distinct areas with two different doses, we achieve an 8-level switching, as shown in Fig. 1b. We demonstrate a promising and practical approach for improved data storage and high-performance computation in SOT-based spintronic devices which opens the door to preferential current-driven magnetisation switching of predetermined areas of the sample, defined down the nm resolution of ion beam microscopy.

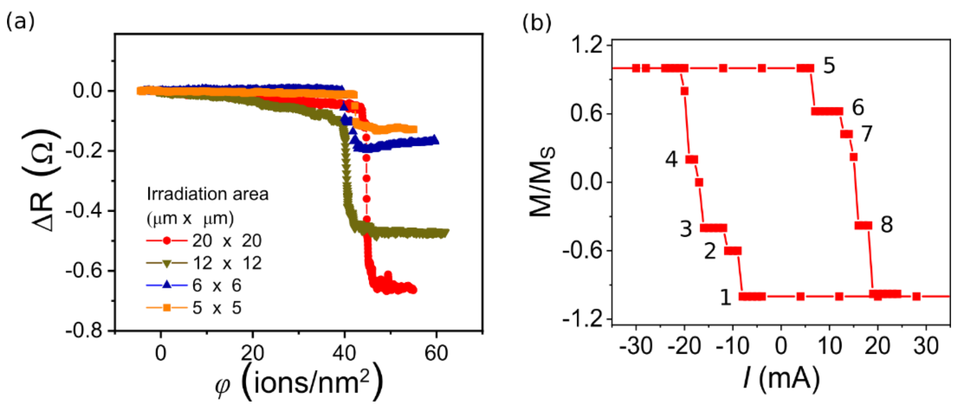

Figure 1 (a) Evolution of in-situ anomalous Hall resistance with irradiation for different exposed area of Hall cross. (b) MOKE acquired SOT induced magnetization switching curve of 8-level switching device under a bias field of 125 mT.

References

[1] C. Chappert *et al.*, "Planar Patterned Magnetic Media Obtained by Ion Irradiation," *Science*, vol. 280, no. 5371, pp. 1919–1922, Jun. 1998, doi: 10.1126/science.280.5371.1919.

Current and angular dependence of bulk spin-orbit torques in Fe_3GeTe_2

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Spin-Orbit torque (SOT) is a mechanism used to control the magnetization of a ferromagnet and is therefore very promising in the field of spintronics [1]. In addition to rather well understood interfacial SOTs [1] occurring at the interface between a ferromagnetic and a non-magnetic layer, there are also bulk SOTs occurring in a single ferromagnetic layer [2].

We investigated the magnitude of SOTs in the 2-dimensional van-der Waals material Fe_3GeTe_2 predicted and shown to exhibit bulk SOTs by Ø. Johansen et al. [3] and F. Martin et. al [2]. We performed magnetic transport measurements with harmonic analysis using the experimental setup depicted in figure 1a). In our experiments we found a clear dependence on the applied current density yielding the magnitude of the SOTs to decrease with the current getting larger as it is shown in figure 1b). We discuss where this current dependence comes from. Furthermore, we measured the angular dependence of the SOTs with respect to the azimuth and the polar angle, Φ and θ of the externally applied magnetic field at various temperatures, see figure 1c). A temperature dependence is observed, decreasing SOTs with increasing temperature. We compare the experimental results to theoretical calculations [4] performed for Fe_3GeTe_2.

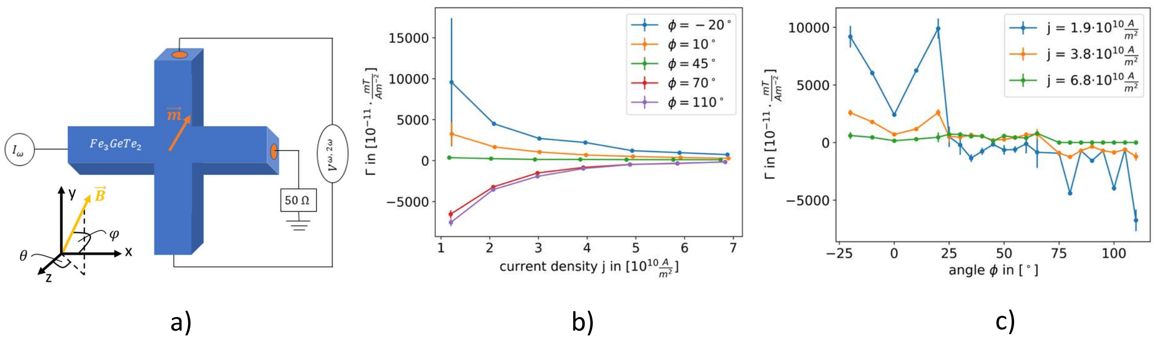

Figure 1: a) Experimental setup of the transport measurements performed. b) Current dependence of the magnitude of the SOTs Γ at various azimuth angles Φ and temperature T = 100 K. c) Angular dependence of Γ of the azimuth angle Φ at various current densities j and temperature T = 100 K.

[1] R. Ramaswamy, J. M. Lee, et al., Appl. Phys. Rev. vol. 5, no. 031107, 2018

[2] F. Martin, K. Lee, et al., arXiv 2107.09420, 2021

[3] Ø. Johansen, V. Risinggård, et al., Phys. Rev. Lett. vol. 122, no. 21, 2019

[4] T. G. Saunderson, D. Go, et al., arXiv 2204.13052, 2022

Phase-Change Controlled Magnetic Tunnel Junction for Multifunctional In-Sensor Computing

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In-sensor computing has been considered as an ideal architecture for sensor-rich platforms (such as autonomous vehicle and intelligent robots) for the advantages in decreasing power consumption and time delay [1]. However, current investigations mainly focus on the sensory processing of a single type of information [2] based on imitating human perception system. In fact, human perception system can sense and process multiple stimuli simultaneously even in a complex environment and small perceptive field. By combining phase-change material VO_2 with magnetic tunnel junction (MTJ), we propose an in-sensor computing device with the ability to sense optical and magnetic information simultaneously. The device could provide a new paradigm for multifunctional sensing of light illumination and magnetic field, which could be applied to the field of intelligent sensing such as electronic skin. Especially, reproducible multiresistance states of device can be realized in response to light illumination and magnetic field. Furthermore, eight reconfigurable logic gates such as AND and OR are achieved based on the two captured information, realizing multifunctional sensory processing within a single device. This device provides more possibilities for the intelligent sensing and the IoT application.

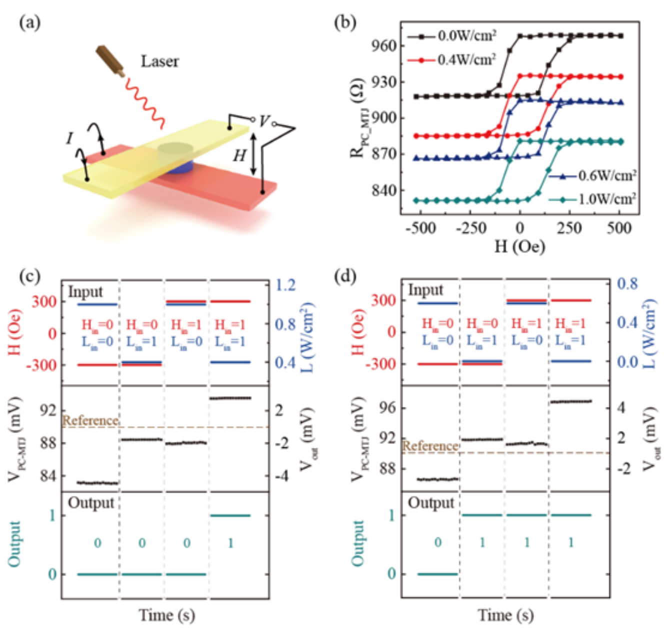

Fig. 1 (a)Schematic of device. (b) sensing optical and magnetic information simultaneously. (c-d) reconfigurable logic gates AND and OR

[1] Yang Chai and F. Zhou, "Near-sensor and in-sensor computing," Nat Electron, vol. 3, no. 11, 2020.

[2] B. Dang, L. Ma, et al., "Physically Transient Optic-Neural Synapse for Secure In-Sensor Computing," IEEE Electron Device Lett., vol. 41, no. 11, 2020.

Spintronics-based Bayesian Binarized Neural Networks for biomedical applications

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Artificial neural networks excel at pattern recognition tasks ranging from identifying objects in an image to natural language translation to predicting protein structures. A severe limitation of conventional artificial neural networks is that they fail to quantify the uncertainty of their predictions. Bayesian neural networks, whose parameters are probabilistic can resolve this issue, however, they are extremely costly to implement using conventional computers. In this work, we propose a spintronics-based implementation of Bayesian networks, where spintronic physics implements the probabilistic nature of Bayesian neural networks intrinsically. We implement a version of such networks whose parameters can take only two values [1]. In our approach, these values correspond to the magnetization state of a nanoscopic magnetic thin film with a domain wall. Thermal fluctuation of the domain wall between two regions of decreased magnetic anisotropy drives the natural stochastic switching between these two states. Learning a pattern recognition task at the network level amounts to modifying the probability of switching. At the device level, this corresponds to tuning the asymmetry between the two states. The voltage-driven magnetoionic effect allows for precise, low-power, non-volatile control of this asymmetry [2], enabling learning pattern recognition tasks. With such implementation, we demonstrate the advantages of using Bayesian networks over their conventional counterparts in quantifying the uncertainty in classifying human blood cell types. These results show the possibility of using the stochasticity of spintronic devices as a tool for handling uncertainty in neural networks, which extends the range of applications of such computing to medical and other critical applications.

[1] R. Pachat et al., Phys. Rev. Appl. 15, 064055, July 2021.
[2] X. Meng et al. ICML’20, art. No. 636, pages 6852-6861, July 2020.

Strain-controlled Domain Wall manipulation into nanowires for sensor applications

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In this study, we address a well-known challenge in magnetic sensor development, which is the effect of packaging-induced strain on the sensor properties[1]. While previously the field operation window has only been studied in idealized operation conditions, in real devices further external factors such as strain play a role.

In this experimental work, we investigate the injection of a 180° domain wall from a nucleation pad into a nanowire, as typically used for domain wall-based sensors, while straining the device along selected directions. Combining our experimental measurements by Kerr microscopy with micromagnetic simulations, we find that strain, regardless of its direction, increases the domain wall injection field due to the magnetoelastic coupling of the magnetic material. The above-described observations can be explained by an effective strain-induced anisotropy in the device [2].

We find additionally that a careful material preparation, comprising of an annealing step, can reduce the effective anisotropy caused by the strain in the magnetic layer. With this we show that a device free of magnetostrictive behaviour can be achieved [3].

As a second part, we consider the behaviour of DWs in these types of sensor devices in the presence of non-uniform strain anisotropy. This is both realized by locally changing the magnetoelastic coupling [4] or with the use of strain gradients in differently strained areas.

References:

[1] Jogschies, Lisa, et al. "Recent developments of magnetoresistive sensors for industrial applications." *Sensors* 15.11 (2015): 28665-28689.

[2] Finizio, Simone, et al. "Magnetic anisotropy engineering in thin film Ni nanostructures by magnetoelastic coupling." *Physical Review Applied* 1.2 (2014): 021001

[3] Masciocchi, Giovanni et al., *Journal of Applied Physics* 130 (2021), 183903

[4] Masciocchi, Giovanni et al. arXiv:2207.02493 (2022)

Zero field Skyrmion nucleation and dynamics in Co Based Synthetic Antiferromagnet

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Skyrmions in synthetic antiferromagnetic (SAF) systems hold great potential to be used in nonvolatile memory and logic devices as they overcome several limitations posed by their counterpart in ferromagnetic systems [1]. Ultra-small skyrmions due to vanishingly small magnetization and dipolar field, and zero effective topological charge are some of the most attractive characteristics predicted for skyrmions in SAF. In this report, we show by fine tuning the sample micromagnetic parameters, through their control by the magnetic layer thickness, SAF multilayers can be optimized to host zero field skyrmion. Using Co as the magnetic film and Pt/Ir as the spacer for RKKY type interaction, we have achieved a very strong antiferromagnetic (AF) coupling (~1T), which is crucial for the current induced dynamics of SAF skyrmions without distortion. By enhancing the perpendicular magnetic anisotropy of the system through modifying the Co thickness we show that room temperature zero field skyrmions are stable in this SAF system. We verify their stability through magnetic force microscopy (MFM) images, where we use very thick magnetic layer coated home-made tips. A large difference in MFM signal contrast between a ferromagnetic and AFM samples confirms the SAF coupling of our samples and associate low effective magnetization. Further we show current induced skyrmions nucleation in nano-tracks. Nucleation is assisted by thermal heating and spin accumulation at the point contact in our fabricated tracks. We observe spin Hall effect assisted motion of skyrmions in these SAF tracks too. This work paves a way towards realization of skyrmionic devices at zero field concerning stacks that are insensitive to magnetic field like ferrimagnets and antifferromagnets.

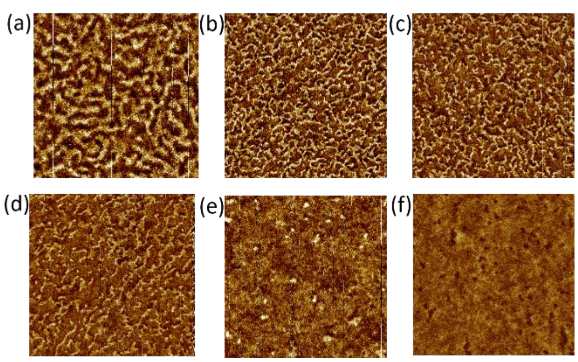

Fig. 1: *(a) MFM image of virgin state of the sample. (b-f) MFM images obtained at zero field after pretreating the sample at 105 mT (b), 115 mT (c), 125 mT (d), 200 mT (e) and -200 mT (f). Isolated skyrmions can be seen in (e) and (f) where opposite pretreated field leads to reversal in skyrmion core orientation.*

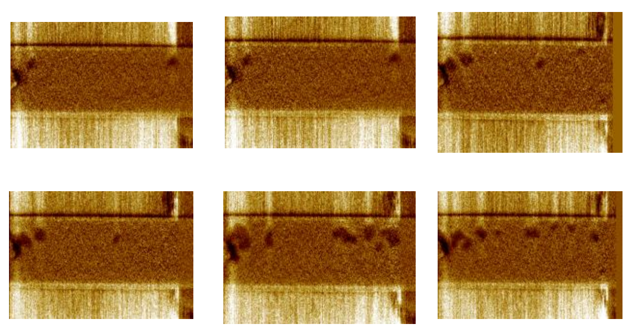

Fig. 2: *Nucleation and motion of magnetic skyrmions in a synthetic antiferromagnetic system by applying a 8.25E11* A/m^2*, 10ns current pulse. The nucleation seems to be due to thermal heating near the point contact and at specific defect sites.*

[1] Zhang, X., Zhou, Y. & Ezawa, M. Magnetic bilayer-skyrmions without skyrmion Hall effect. Nat. Commun. 7, 10293 (2016).

This work is supported by a public grant overseen by the French National Research Agency (ANR) as part of the "Investissements d'Avenir" program (Labex NanoSaclay, reference: ANR-10-LABX-0035).

Opto-electric imaging of nickel oxide

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Reliance on data storage devices has become an increasingly prevalent part of the modern knowledge-sharing society in the digital era. One way to overcome the speed and density limitations of existing memory devices based on ferromagnets (FMs) is to shift the paradigm from using FMs towards antiferromagnets (AFMs). AFMs have increased information density and reading/writing speed capabilities due to the presence of magnetic microscopic ordering, but absence of net macroscopic magnetization. The latter property, however, makes reading/writing AFMs notoriously difficult and prevents AFMs from widespread application.
A solution for the AFM reading challenge based on optical methods [1] is a promising candidate, since it bridges the gap between spintronic storage applications and photonic communication solutions. In this work, opto-electric imaging techniques are investigated on microstructured devices of thin film magnet/heavy metal bilayers, which enable the electrical detection of the magnet's ordering parameter when locally excited by a laser pulse. It is demonstrated experimentally (Figure 1) that this method can be used to read the magnetic state of the ferrimagnet yttrium iron garnet (YIG). The same experiments on the AFM NiO are inconclusive, complicated by the presence of parasitic artifacts. With simulations (Figure 2) it has been confirmed though that a spatially varying Seebeck coefficient dependent on the device geometry is capable of reproducing the experimental data. It is furthermore argued that the sidewall roughness of the devices could be responsible for the variation of the Seebeck coefficient [2].

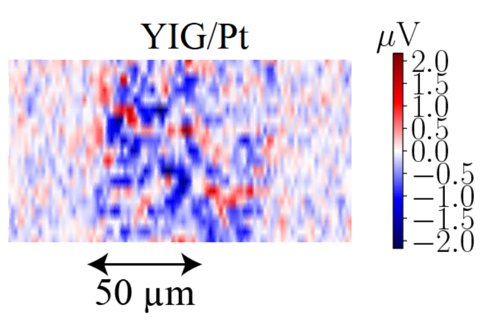

Figure 1: Domain pattern obtained by opto-electric imaging on a YIG/Pt sample in zero-field conditions, with red and blue regions corresponding to 180° domains.

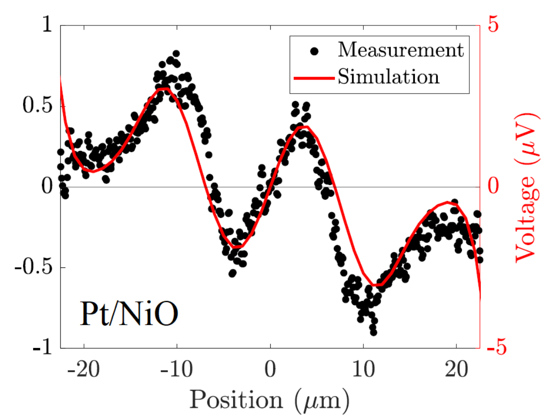

Figure 2: Comparison of measurement data from opto-electric imaging on Pt/NiO with simulation data, assuming a spattialy varying Seebeck coefficient.

[1] I. Gray, T. Moriyama, *et al.*, *Phys. Rev. X*, vol. 9, 4 2019.

[2] W. Sun, H. Liu, *et al.*, *J. Appl. Phys.*, vol. 110, 8 2011.

Thermal skyrmion diffusion under alternating excitation

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Magnetic skyrmions, topological spin textures appearing as quasi-particles in thin magnetic films, are considered promising candidates for the implementation of probabilistic computing devices since they respond strongly nonlinear to external stimuli and feature inherent multiscale dynamics [1].
The implementation of such reservoir computing relies on thermal excitation of the magnetic skyrmions within thin films exhibiting pinning due to sample defects [2]. The combination of skyrmion diffusion and current-induced motion has been shown to be useful in Brownian reservoir computing devices [3] and other probabilistic computing applications. As large sample-specific defects create spatial bias in such systems, a depinning procedure is needed for a space-independent motion.
To reach a regime of near free diffusion, we propose and experimentally demonstrate depinning applying alternating electric and magnetic fields to the sample. In particular, we show that the energy landscape is effectively flattened and diffusion is drastically enhanced for sufficient excitation. This effect can therefore be useful to reduce pinning effects and thus accelerate non-conventional computing devices as well as to lower thresholds for current-induced skyrmion motion due to smaller pinning effects.

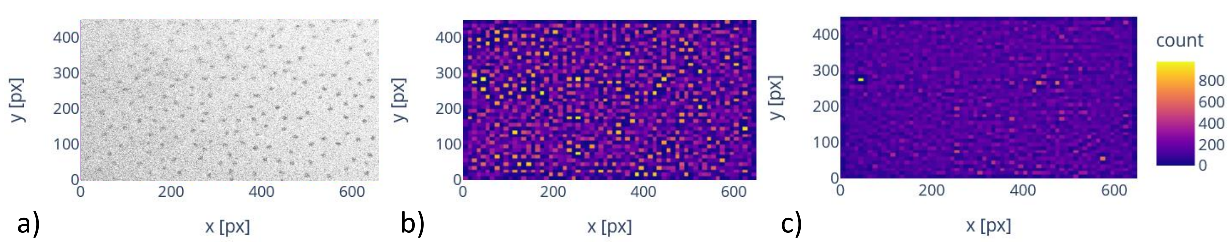

Figure 1: Skyrmion localisation probabilities. Kerr microscopy images of a thin magnetic film with multiple skyrmions (dark grey) (a). b) shows exemplary the probability density of finding a skyrmion at a certain location without, d) with strong excitation for a measurement time $\Delta t = 60s$.

[1] D. Prychynenko, M. Sitte, *et al.*, *Physical Review Applied*, vol. 9, no. 1, 31, 2018.

[2] R. Gruber, J. Zázvorka, *et al.*, *Nature Communications*, vol. 13, no. 1, 6, 2022.

[3] J. Zázvorka, F. Jakobs, *et al.*, *Nature Nanotechnology*, vol. 14, no. 7, 2019.

Voltage induced magneto-ionic interactions controlling magnetic properties of synthetic antiferromagnets

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Voltage control of magnetic properties in spintronic devices is the device-compatible and energy-efficient way for future storage applications [1]. This approach can be realized with the advantages of a synthetic antiferromagnet (SAF) system, which provides higher thermal stability and a wide dynamic range, e.g. high domain wall velocities for nearly compensated SAFs [2] when integrated into MRAM devices.

To realize an effective voltage-controlled spintronic device, we have grown a SAF thin film material stack by magnetron sputtering consisting of two ferromagnetic layers coupled by a non-magnetic spacer layer via the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction. A thermodynamically stable skyrmion state at elevated temperatures is achievable in this stack [3]. With room temperature voltage-controlled magneto-ionic effects, we focus on the modulation of the magnetic properties in this system, i.e., the control of the compensation ratio, the perpendicular magnetic anisotropy, and the antiferromagnetic RKKY coupling strength.

[1] T. Nozaki *et al*., Micromachines 10(5), 327 (2019).
[2] Y. Guan *et al*., Nat. Commun. **12,** 5002 (2021).
[3] T. Dohi, *et al*., Nat. Commun **10,** 5153 (2019).

Spin pumping into a two-dimensional electron system with spin-orbit couplings

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Two types of spin-orbit couplings, Rashba-type and Dresselhaus-type [1], are known to appear in two-dimensional electron systems formed in semiconductor heterostructures. By combining these two spin-orbit couplings, some characteristic spin-related phenomena, such as persistent spin helix states [2], appear. Although spin injection into systems with Rashba spin-orbit coupling has been studied [3], there have been few studies on the coexistence of Rashba and Dresselhaus type spin-orbit couplings.

In our study [4], we considered a junction composed of a ferromagnetic insulator and a two-dimensional electron gas (2DEG) with these two types of spin-orbit couplings and studied a situation in which a spin current is injected into the 2DEG by irradiating microwaves to the ferromagnetic insulator (FI) (Fig. 1-a). The Rashba- and Dresselhaus-type spin-orbit couplings induces an anisotropic effective magnetic field acting on the electrons (Fig. 1-b). Our calculations show that the magnitude of the Gilbert damping enhancement depends on the angle of magnetization in the FI, reflecting this property (Fig. 1-c). Furthermore, a closer look at this magnetization angle dependence shows that in the low (high) frequency range, the magnitude of the increase in Gilbert damping is largest when the effective magnetic field and the magnetization in the FI are perpendicular (parallel) (Fig. 1-c). This means that elastic (spin-flip) processes are dominant on the low (high) frequency side. These results suggest that the observation of the magnetization angle dependence of the Gilbert damping enhancement can provide information on the spin texture on the Fermi surface of the 2DEG.

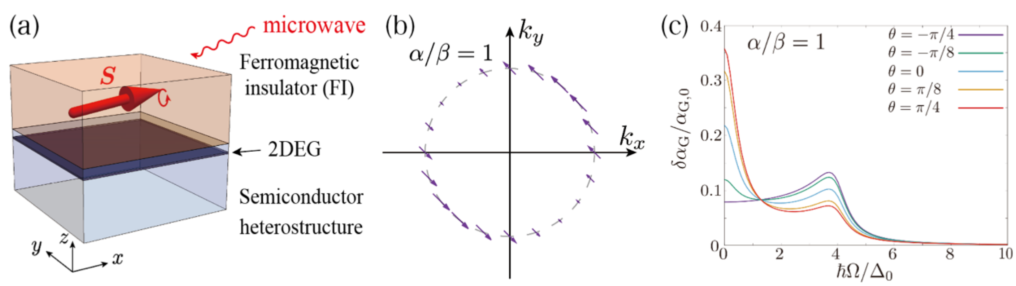

Figure 1: (a): Setup. (b): Effective magnetic field produced by spin-orbit couplings. α and β are constants indicating the magnitudes of the Rashba-type and Dresselhaus-type spin-orbit couplings.
(c): Results. Increase in Gilbert damping (vertical axis) as a function of microwave energy (horizontal axis) and the angular dependence of the magnetization in the *x*-*y* plane in a ferromagnetic insulator (θ).

[1] R. Winkler, Springer Tracts in Modern Physics; Springer: 2003; Vol. 191.
[2] B. A. Bernevig, et al., Phys. Rev. Lett. **97**, 236601 (2006).
[3] H. Nakayama, et al., Phys. Rev. Lett. **117**, 116602 (2016).
[4] M. Yama, M. Tatsuno, T. Kato, and M. Matsuo, Phys. Rev. B **104**, 054410 (2021).

Spin Manipulation by Giant Valley-Zeeman Spin-Orbit Field in Atom-Thick WSe_2

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The phenomenon originating from spin-orbit coupling (SOC) provides energy-efficient strategies for spin manipulation and device applications[1]. The broken inversion symmetry interface and resulting electric field induce a Rashba-type spin-orbit field (SOF), which has been demonstrated to generate spin-orbit torque for data storage applications. The low symmetry of 2D materials provides new possibilities for efficient spin manipulation[2]. In this study, we found that spin flipping can be achieved by the valley-Zeeman SOF in monolayer WSe_2 at room temperature, which manifests as a negative magnetoresistance in the vertical spin valve[3]. Quantum transmission calculations based on an effective model near the K valley of WSe_2 confirm the precessional spin transport of carriers under the giant SOF. In particular, the valley-Zeeman SOF-induced spin dynamics was demonstrated to be tunable with the layer number and stacking phase of WSe_2, which provides a novel strategy for spin manipulation and can benefit the development of ultralow-power spintronic devices.

Reference:

[1] A. Manchon et al., NAT MATER 14, 871 (2015).
[2] H. Yuan et al., NAT PHYS 9, 563 (2013).
[3] X. Wang et al, Appl. Phys. Rev., 9, 31402 (2022).

Quantum oscillations in the Kagome superconductor CsV_3Sb_5

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The recently discovered layered Kagome metals AV_3Sb_5 (A = K, Rb, Cs) exhibit a unique combination of nontrivial band topology, competing for the charge- and superconducting orders with clear signatures of electron correlations. Using magnetization, resistivity, thermal expansion, magnetostriction and heat capacity, we have investigated the normal- and superconducting-state properties of single crystals of the kagome superconductor CsV_3Sb_5. The magnetization and magnetostriction data show clear signatures of quantum oscillations with at least two distinct frequencies. These are much less evident in the heat capacity. Combining the results from these thermodynamic probes and transport measurement, we discuss the nature of the Fermi surface and the interplay between the charge order and superconductivity.

Electric field control of chiral magnetic textures in multilayer films with perpendicular magnetic anisotropy

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The manipulation of the interfacial magnetic anisotropy *via* an electric field is an active field of research, as it is a promising route toward the realisation of low-power spintronic devices. The largest effects of an electric field on the perpendicular magnetic anisotropy (PMA) have been obtained by triggering the migration of ionic species across a dielectric layer toward or away from a ferromagnet-oxide interface [1]. This magneto-ionic effect leads to a nonvolatile modification of the magnetic properties, as opposed to the volatile effect obtained by electron accumulation or depletion.

We will first present the effect of the gate voltage on the magnetic anisotropy of a series of Pt/Co/MOx (M=Al, Tb) trilayers. In these trilayers, both Co interfaces contribute to the PMA and the contribution at the Co/MOx interface strongly depends on its oxidation state. The trilayers are covered with a high-k ZrO_2 or HfO_2 dielectric layer, acting as an oxygen ion conductor, and with micrometer-size Pt electrodes.

The application of a negative/positive voltage triggers the migration of oxygen ions towards/away from the Co/MOx interface, leading to a local modification of the magnetic anisotropy. The PMA can be modified locally, so that under the electrodes the magnetisation easy-axis can be changed from out-of-plane (OOP) to in-plane (IP) in a reversible and nonvolatile way. Starting from a OOP saturated state, magnetic textures such as stripe domains or skyrmion bubbles can be stabilised by the gate voltage [2,3] (Figure 1(a,b)).

In a second set of experiments, we studied the effect of the gate voltage on the fielddriven dynamics of chiral Néel walls in ferrimagnetic Pt/Co/Tb trilayers. We will show that a negative gate voltage leads to the partial oxidation of the Tb layer, and as a consequence to a

variation of the effective magnetisation, the PMA and the interfacial Dzyaloshinskii-Moriya interaction (DMI). The variation of these magnetic parameters is at the origin of a huge variation of the domain wall (DW) velocity. For large magnetic fields, the DW speed varies from 10 m/s in the pristine state to 225 m/s after gating [4] (Figure 1(c)).

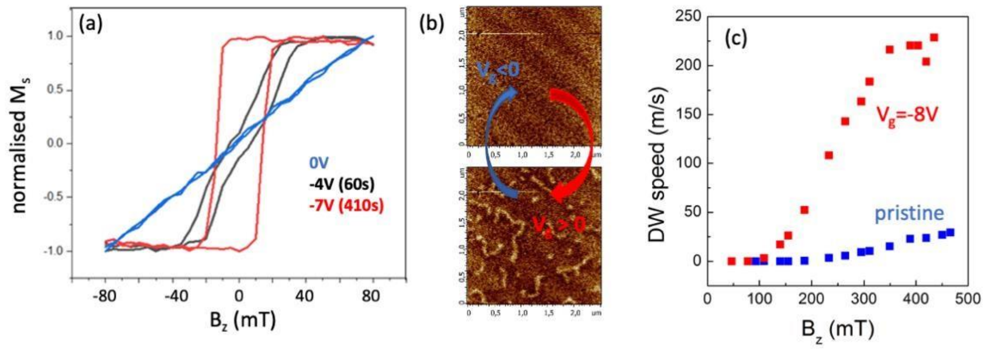

Figure 1: (a) polar Kerr hysteresis loops for Pt/Co/TbOx before and after application of negative gate voltage; (b) MFM images showing the reversible change between OOP saturated state and stripe domains plus skyrmion bubble state with gating (c) DW speeds in Pt/Co/Tb before and after gating. In both cases a ZrO_2 ionic conductor was used as dielectric layer.

[1] C. Bi et al. Phys. Rev. Lett. 113, 267202 (2014).
[2] A. Fassatoui et al. Phys. Rev. Appl. 14, 064041 (2020).
[3] A. Fassatoui *et al.* Small 210242 (2021).
[4]Balan et al. Phys. Rev. Appl. 18, 034065 (2022)

Imaging the magnetic structure of antiferromagnetic PtMn

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Antiferromagnetic materials (AFM) are gaining increasing interest in the recent years because of their high potential for new spintronic devices with very high bit packing densities and ultrafast dynamics. [1] PtMn is widely used, especially for pinning layers in magnetic devices. [2] It has a CuAu-I type structure with a high bulk Néel temperature of 975 K. [3] THz spin dynamics [4] and periodic chiral structures [5] were predicted in PtMn. However, to use it as the active layer of spintronic devices, the first crucial step is to read out its magnetic state. This was achieved now by imaging the domains with x-ray magnetic linear dichroism (XMLD) photoemission electron microscopy (PEEM) (see Fig. 1 b). Additionally, the average domain size was determined for PtMn films of 40 nm thickness on MgO (001) from a Fast Fourier transform (FFT) of the XMLD images. It showed a distinct ring, corresponding to an average domain periodicity of approximately 700 nm (see Fig. 1 c).

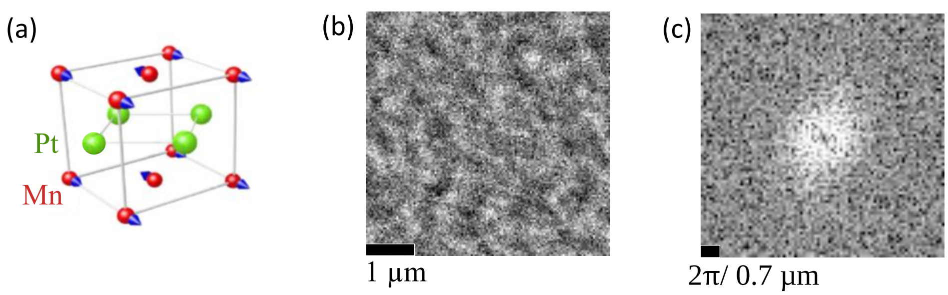

Figure 1: (a) Crystal structure of PtMn from [6]. The blue arrows indicate a possible spin orientation. (b) Domain structure of MgO (001)/ PtMn (40 nm)/ Al (1.6 nm), imaged with XMLD PEEM at 639.9 eV. The contrast was obtained from the difference between the linear horizontal (LH) and linear vertical (LV) polarization as (LH – LV)/(LH + LV). (c) Fast Fourier transform (FFT) of the XMLD image in (b).

[1] V. Baltz et al., Rev. Mod. Phys. **90**, 015005 (2018).
[2] G.W. Anderson et al., J. Appl. Phys. **87**, 5726 (2000).
[3] L. Pál et al., J. Appl. Phys. **39**, 538 (1968).
[4] K. Kang et al., ArXiv:2112.13954 [Cond-Mat] (2021).
[5] Md.R.K. Akanda et al., Phys. Rev. B **102**, 224414 (2020).
[6] Sklenar et al., AIP Adv. **6**, 055603 (2016).

A micromagnetic theory of skyrmion lifetime in ultrathin ferromagnetic films

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Magnetic skyrmions are a characteristic example of topological solitons existing at nanoscale. While the fundamental object for applications is an individual skyrmion in a homogeneous ferromagnetic environment, for topological reasons it cannot be created or annihilated by a continuous transformation from the ferromagnetic state. This transition is however enabled by the discrete nature of the condensed matter as observed experimentally. The detailed physical mechanisms of skyrmion annihilation have been investigated at the nanoscale using atomic spin simulations combined with methods of finding the minimum energy path and harmonic transition state theory. However, there are limitations to the atomistic simulations. First, they are computationally expensive, which limits the accessible skyrmion sizes (usually below 5 nm in diameter) and the physical parameter ranges that can be explored. Second, the obtained results depend on the microscopic details that are not necessarily known or controlled in the case of nanocrystalline systems. Under these circumstances, there is clearly a need for a more coarse-grained theory that would provide universal relations between the skyrmion lifetime and the material parameters. Moreover, it is reasonable to expect that under many physically relevant conditions the microscopic details do not play a dominant role for fluctuation-driven skyrmion collapse.

We will present a theory of skyrmion lifetime based on the continuum field theory and derive the expressions for both the energy barrier and the attempt frequency as functions of all the material parameters [1]. Starting with the stochastic Landau-Lifshitz-Gilbert partial differential equation, we first derive several integral identities associated with the fundamental continuous symmetry groups of the exchange energy. Then, in the exchange dominated regime, we carry out a finite dimensional reduction of the stochastic skyrmion dynamics and obtain a system of stochastic ordinary differential equations for the skyrmion radius and angle. Finally, in the small thermal noise regime we use the obtained equations to calculate the Arrhenius rate, including the prefactor, by interpreting the skyrmion collapse event as “capture by an absorber” for the skyrmion radius at the atomic scale.

[1] A. Bernand-Mantel, C. Muratov and V. Slastokikov, A micromagnetic theory of skyrmion lifetime in ultrathin ferromagnetic films PNAS 119 e2122237119 (2022)

Simultaneous detection of SMR and current-induced SSE within antiferromagnetic insulators

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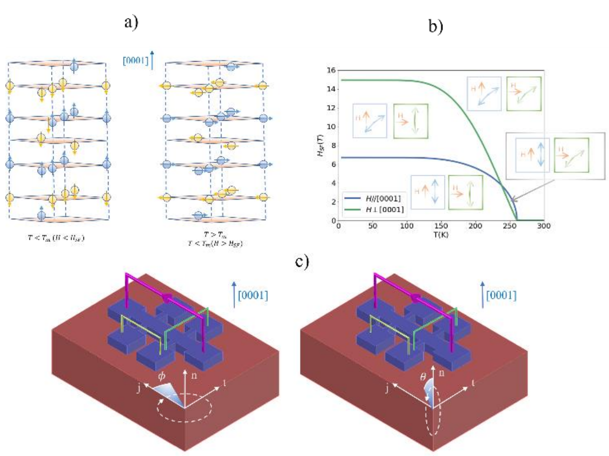
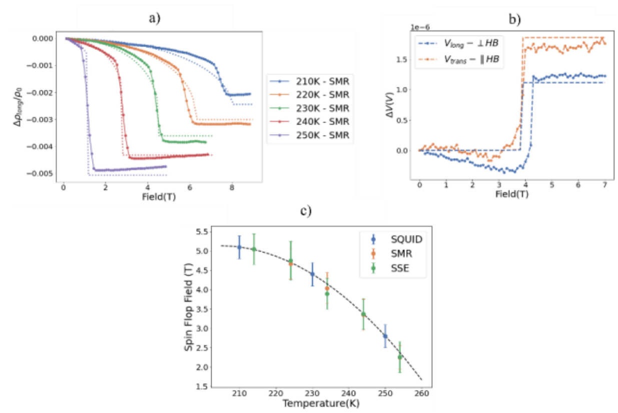
Antiferromagnetic materials are a potentially promising avenue with regard to spintronic applications – with no overall magnetic moment, they are insensitive to magnetic perturbations, and hence offer robust magnetic storage possibilities. Their ultrafast magnetisation dynamics also suggest ultrafast magnetic storage devices may be feasible. However, the overall zero magnetisation and the insensitivity to magnetic fields makes probing the magnetic state of such materials more challenging. Two electrical methods have been demonstrated: the spin Hall magnetoresistance (SMR) and the spin Seebeck effect (SSE). In both of these effects the spin-to-charge conversion is achieved in an adjacent Pt thin film via the inverse spin Hall effect. In this work we characterise these two effects simultaneously in the same $\alpha{-}Fe2O3$(0001)/Pt bilayer below the Morin transition. We use lock-in detection, where the 1st and 2nd harmonics measure respectively the SMR and the SSE.



a) Schematic of magnetic moment directions within different layers of hematite unit cell above and below the Morin Transition. b) Phase diagram for hematite – for fields applied both along and perpendicular to the easy axis ($T < T_m$), there is a spin flop transition, the latter of which is a consequence of the DM interaction observed in Hematite. c) Setup used in this experiment – 1st and 2nd Harmonic Voltages can be determined simultaneously using a lock in amplifier.



a) Example of 1st Harmonic Lock In Data acquired ($H \perp [0001]$), with predicted fit obtained using SQUID data shown. b) Example of 2nd Harmonic Lock In Data acquired ($H \parallel [0001]$). c) Demonstrating compatibility between Spin Flop Transition fields acquired via SQUID, SMR and SSE measurements.

Ultrafast imaging of heat assisted magnetization switching in Lu substituted iron garnet

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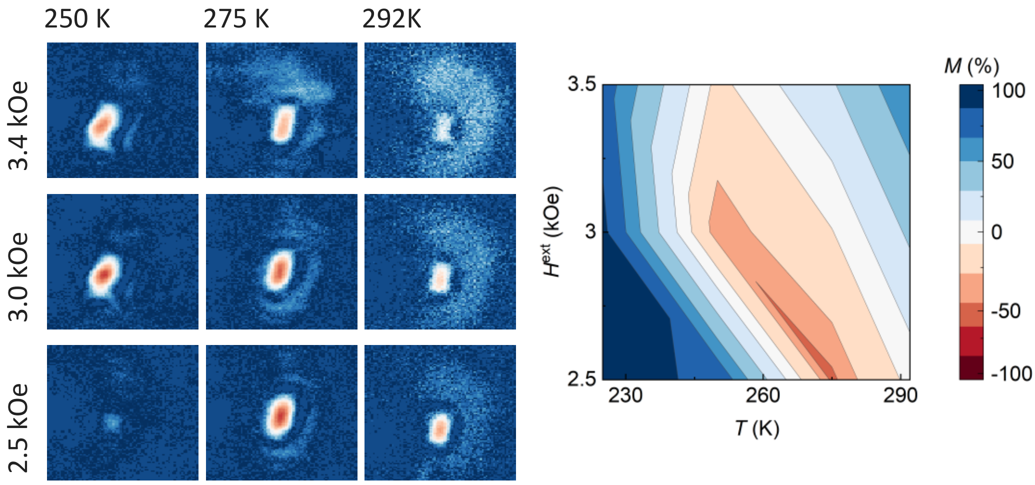
Ultrafast laser-induced heating of ferrimagnetic iron garnet in external magnetic field triggers magnetization precessional dynamics with very large amplitude. In particular, the studied sample is Lu substituted ferrimagnetic iron garnet film $(Bi,Lu)_3(Fe,Ga,Al)_5O_{12}$. Magnetic properties of the compound are defined by the spins of Fe^{3+} ions in the octahedral and the tetrahedral sites, which form two nonequivalent antiferromagnetically coupled spin subattices, respectively [1]. In our study we employed pump-probe technique, where pump pulse with the central wavelength 625 nm was focused (d = 100 μm) on the sample. Unfocused 800 nm probe pulse was delayed from pump up to 8 ns and produced the magneto-optical image of the sample. Such a pump pulse heats up the sample reducing the anisotropy field and thus resulting in magnetization precession around new equilibrium orientation. The dynamics is studied as a function of magnetic field, laser fluence and sample temperature. Exploring the whole space of parameters, we identify the conditions for which the amplitude of the precession is high enough to achieve heat-assisted magnetic recording. Figure 1 shows the magnetization changes obtained with the CCD camera in 8 ns after the lattice was excited with femtosecond laser pulse. It is seen that the dynamics of the largest amplitude is achieved either at high fields and low temperatures or at high temperature and low fields. We propose a model that can explain these results.



The photographs are representing magnetic state of the system (left). Phase diagram of the pump-induced magnetization switching (right).

[1] V.J. Fratello, S.E.G. Slusky, et al., Journal of Applied Physics 60, 2488 (1986)

Magnetic and thermoelectric properties of Bi-substituted $La_{0.95-x}Bi_xSr_{0.05}CoO_3$

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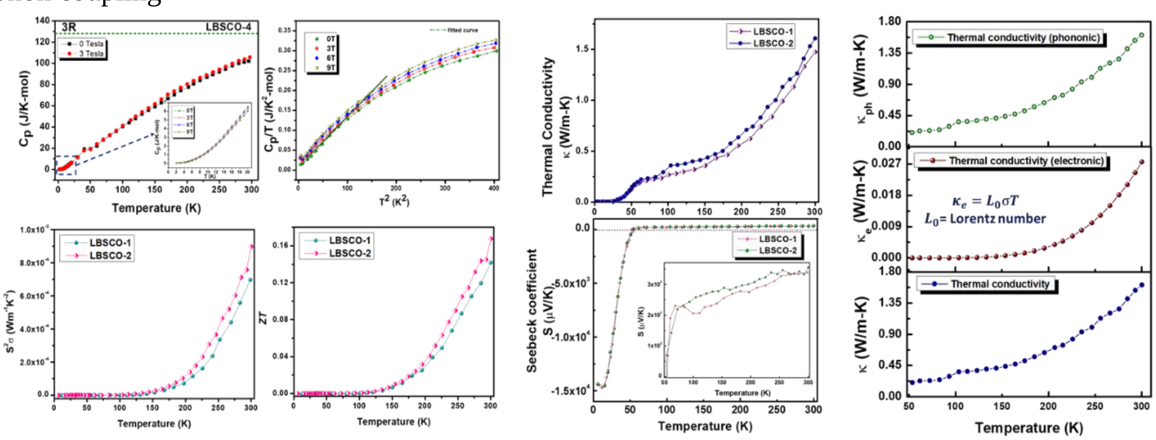
We present the results of a comprehensive investigation of electric and thermal transport properties of polycrystalline Bi substituted $La_{0.95-x}Bi_xSr_{0.05}CoO_3$ for $x = 0$, 0.1 and 0.2 (LBSCO-0, 1 & 2). The electrical resistivity reflects the semiconducting nature with interesting n-type to p-type transition ~ 52K for LBSCO-1 and LBSCO-2 samples. The substitution of higher atomic weight elements Bi at La site drastically affects overall thermal conductivity by reducing the lattice contribution (κ ~ 0.12W/m-K at T = 50K) and also enhance the Seebeck coefficient (S ~ 354$\mu V/K$). The increase in the resistivity and Seebeck coefficient for Bi-substituted system is related to the decrease in the available charge carrier concentration (~ 5.12 × $10^{20}/cm^3$). The phonon mediated charge transport via phonon drag effect below 50K and a large increment in ZT ~0.17 at RT for LBSCO-2 composition has been observed that is 1-order larger to pristine undoped LBSCO-0 and even higher to the other existing cobaltite's-based thermoelectric choice **[1,2]**.

Keywords: Seebeck coefficient, thermal conductivity, heat capacity, thermoelectric, oxide, electron-phonon coupling



References

[1] Jian He and Terry M. Tritt, Science 357, eaak9997 **(2017)**.

[2] Christopher J. Vineis, Ali Shakouri, Arun Majumdar, and Mercouri G. Kanatzidis Adv. Mater. 22, 3970–3980 **(2010)**.

Magnetization Reversal Process in Bi-modulated FeCo Cylindrical Nanowires

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The understanding and control of magnetic structures is essential for the development of novel applications in several areas such as biomedicine, data storage, microwave technologyn [1]. Cylindrical nanowires offer an alternative to nanostripes due to geometry induced effects such as the suppression of the Walker breakdown [2]. Cylindrical geometry stabilizes a number of novel magnetic textures such as Bloch Point Domain Walls (BPDW) and vortex and skyrmion tubes. Especially interesting are the modulated cylindrical nanowires with variation in magnetization or diameter since complex configuration can be found [3]. In this work, the magnetization reversal process of a cylindrical nanowire modulated in diameter is investigated by Variable Field Magnetic Force Microscopy (VF-MFM) and non-standard 3D mode imaging techniques [4]. These results will be compared with the previous Magneto-Optical Kerr Effect (MOKE) measurements [5] and the preliminary studies using Photo Emission Electron Microscopy and X-ray Magnetic Circular Dichroism (PEEM-XMCD) techniques. The experimental results, together with micromagnetic simulations reveal a complex magnetization reversal process, mediated by the thin segment and the formation of a vortex tube in the thick segment.

[1] M. Vázquez, in *Magnetic nano-and microwires: design, synthesis, properties and applications*, 2015.

[2] R. Hertel, in *Spin*, World Scientific, vol. 3, 2013.

[3] C. Bran, J. A. Fernandez-Roldan, *et al.*, *Nanomaterials*, vol. 11, no. 3, 2021.

[4] M. Jaafar, L. Serrano-Ramón, *et al.*, *Nanoscale research letters*, vol. 6, no. 1, 2011.

[5] J. García, J. A. Fernández-Roldán, *et al.*, *Nanomaterials*, vol. 11, no. 11, 2021.

A micromagnetic study on the impact of the Inverse Faraday Effect on domain-wall dynamics

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The migration towards the new generation of memory and logic devices can potentially be influenced by our understanding and ability to control domain wall (DW) dynamics at the nanoscale [1,2]. At the same time, light-matter interaction holds the key to the fastest magnetisation processes observed so far. [3] The application of ultrashort circularly-polarised laser pulses has been seen capable of inducing DW motion with the Inverse Faraday Effect (IFE) playing one of the most important roles.

The IFE is traditionally modeled as an additional effective field acting in the direction of the light propagation axis [4] while previous ab-initio work describes it in terms of an induced helicity-dependent magnetic moment or torque. [5] To understand its role in driving DW dynamics, we employ high temperature micromagnetics based on the Landau-Lifshitz-Bloch equation. [6] Assuming a 180^0 Néel wall, we induce an initial magnetisation modulus gradient across the DW and explore the possibility to convert the subsequent longitudinal relaxation of the spins into a translational motion of the Néel wall in the absence of any additional field, torque or thermal gradient. We show that under the action of the IFE, the DW displaces to the region where the magnetisation length was reduced, similar to the action of spin-Seebeck and MCD effects. We compare this method with the field and torque actuation, investigating the DW displacement and velocity as a function of intrinsic damping and electron temperature.

Our results display the DW motion is qualitatively identical within the three IFE pictures, showcasing the final displacement is proportional to the electron temperature while an increase in intrinsic damping leads to an increase of the DW velocity without affecting the final displacement. We further show how in the presence of the Dzyaloshinskii-Moriya interaction, it is possible to augment the DW motion and achieve larger as well as faster DW displacements even under the application of one laser pulse.

References

[1] S. S. P. Parkin, M. Hayashi and L. Thomas, Science, vol. 320, no. 5873, 2008.
[2] D. A. Allwood, G. Xiong et al., Science, vol. 309, no. 5741, 2005.
[3] A.V. Kimel and M. Li, Nat. Rev. Mater., vol. 4, no. 3, 2019.
[4] K. Vahaplar, A. M. Kalashnikova et al., Phys. Rev. B, vol. 85, no. 104402, 2012.
[5] F. Freimuth, S. Blügel, and Y. Mokrousov, Phys. Rev. B, vol. 94, no. 144432, 2016.
[6] U. Atxitia, O. Chubykalo-Fesenko et al., Appl. Phys. Lett., vol. 91, no. 232507, 2007.

Spin-Hall Magnetoresistance in quasi-two-dimensional antiferromagnetic insulator/metal bilayer systems

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Spin Hall magnetoresistance (SMR) is a magnetoresistance induced by combination of spin Hall effect and inverse spin Hall effect in a bilayer system composed of a normal metal (NM) and a magnetic insulator (Fig. 1). The SMR has been observed in NM/ferromagnetic insulator (FI) [1] and NM/antiferromagnetic insulator (AFI) bilayers [2] and has been attracting much attention as a useful probe of the magnetic states in magnetic insulators.

Although a microscopic theory for SMR has been constructed recently [3], actual calculation of the SMR signal was performed only by the spin-wave approximation, which is not applicable to a high-temperature region. In this presentation, we show numerical results of the SMR signal using the quantum Monte Carlo method which can treat AFI in an unbiased way [4]. We present how the SMR depends on temperature, thickness of the AFI layer, the amplitude of the spin, and randomness of exchange interactions. We also discuss on comparison with analytic calculation of high temperature expansion. Our work provides a useful starting point for interpretation of the SMR measurement on quasi-two-dimensional magnetic compounds.

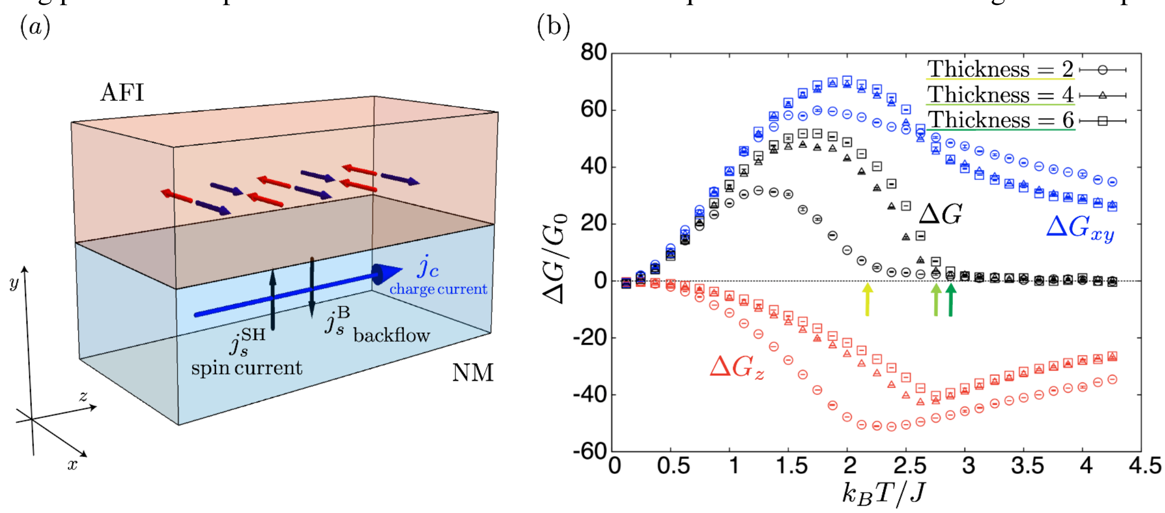

Figure 1: (a): Setup of SMR. (b): Temperature dependence of the spin conductance for the S=1 on a 16×16×W cubic lattice (W=2,4,6) and green arrow shows transition temperature by fitting staggered magnetization.

[1] H. Nakayama et al., Phys. Rev. Lett. **110**, 206601 (2013).
[2] D. Hou et al., Phys. Rev. Lett. **118**, 147202 (2017).
[3] T. Kato et al., Phys. Rev. B **102**, 094437 (2020).
[4] T. Ishikawa, M. Matsuo, and T. Kato, arXiv:2208.08096 (2022).

Proximity-induced ferromagnetism in spin-orbit semimetal $SrIrO_3$

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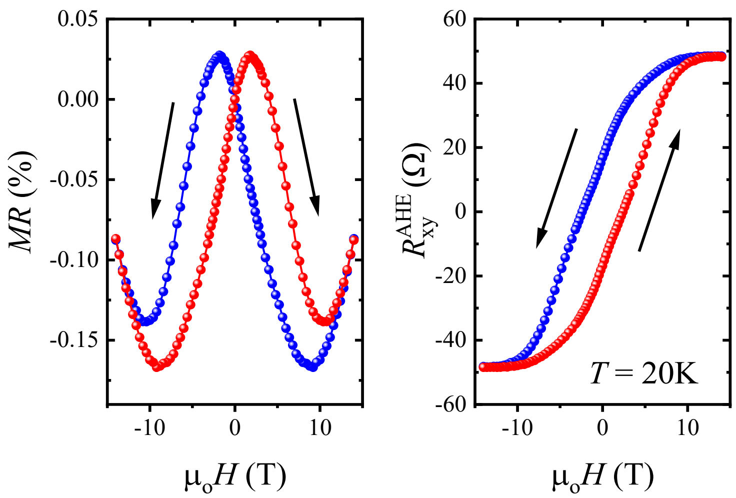
Artificially synthesized transition metal oxide based heterostructures (HSs) and interfaces offer great potential to functionalize novel quantum states that are otherwise absent in their constituent bulk counterparts. The complex interplay between lattice, charge, orbital and spin degrees of freedom provides additional knobs to control and manipulate these states. In this regard, a heavy metal(semimetal) and a ferromagnetic insulator HSs have recently demonstrated very promising results. Here, we report the observation of proximity-induced ferromagnetic state in SrIrO3 (SIO) in a HS consisting of SIO, a strong spin-orbit semimetal [1] and LaCoO3 (LCO) [2], a ferromagnetic insulator. Insulating LCO allows us to probe magnetism in SIO selectively using magnetotransport measurements. We observe anomalous Hall effect, negative magnetoresistance and four-fold anomalous magnetoresistance [3], evidencing the ferromagnetic state with (100) magnetic easy axis direction.



[1] M. A. Zeb and H.-Y. Kee, Phys. Rev. B 86, 085149 (2012).
[2] D. Fuchs *et al.*, Phys. Rev. B2007, 75, 144402
[3] A. K. Jaiswal et al., Adv. Mater. 34, 2109163 (2022).

Topological Hall effect in magnetic skyrmions in Pd/Fe/Ir

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The topological Hall effect (THE) provides an efficient way of detecting skyrmions. This work comprises a theoretical and computational study of the topological Hall effect [1] in magnetic skyrmions, which are formed in ultrathin film Pd/Fe/Ir(111) [2,3]. Employing the non-collinear spin-density-functional theory and the full-potential relativistic Korringa-Kohn-Rostoker (KKR) Green function method we investigate the scattering properties of electrons off skyrmions. We present calculations of the resistivity and the topological Hall angle, which were carried out combining the KKR method with the semiclassical Boltzmann transport equation [4]. We discuss the dependence of the topological Hall angle on additional electron scattering, modelled as a disorder broadening. The effect of the skyrmion size on the Hall angle is also analyzed. Our findings predict that the THE is significantly affected by the degree of disorder of the sample, as well as the skyrmion size.

This work was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the HFRI PhD Fellowship grant (No. 1314). Part of the work was performed under the Project HPC-EUROPA3 (HPC17CTZOF), with the support of the EC Research Innovation Action under the H2020 Programme; in particular, A.K. gratefully acknowledges the support of Prof. S. Blügel, Forschungszentrum Jülich, and the computer resources and technical support provided by HLRS. This work was supported by computational time granted from the Greek Research and Technology Network (GRNET) in the National HPC facility – ARIS – under project ID pr009040_thin-TopMagX2.

[1] K. S. Denisov, I. V. Rozhansky, M. N. Potkina, I. S. Lobanov, E. Lahderanta, and V. M. Uzdin, Phys. Rev. B, vol. 98, 214407, 2018.
[2] N. Romming, C. Hanneken, M. Menzel, J. E. Bickel, B. Wolter, K. Bergmann, A. Kubetzka, and R. Wiesendanger, Science, vol. 341, 6146, 2013.
[3] D.M. Crum, M. Bouhassoune, J. Bouaziz, B. Schweflinghaus, S. Blügel, and S. Lounis, Nat. Comm., vol. 6, 8541, 2015.
[4] https://jukkr.fz-juelich.de/

Effect of anisotropy dispersion on FMR dependences in strained $Y_3Fe_5O_{12}$ thin films

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We report on the correlation of structural and magnetic properties of $Y_3Fe_5O_{12}$ (YIG) layers deposited on $Y_3Al_5O_{12}$ substrates using pulsed laser ablation [1]. The recrystallization of YIG on the lattice-mismatched substrate can result in different film properties when compared to the high-temperature deposition. We observe an unexpected formation of interfacial tensile strain and consequently strain-induced anisotropy contributing to the perpendicular magnetic anisotropy. Moreover, the epitaxial strain has a significant impact on FMR linewidth which is significantly increased in comparison to YIG film deposited on the $Gd_3Ga_5O_{12}$ substrate. Notably, the linewidth dependency on frequency has a negative slope. The unusual linewidth behavior is explained within the proposed anisotropy dispersion model. Good agreement of experimental findings with theoretical predictions suggests that the anisotropy axis is tilted from the film normal and dispersed. We conclude that strain homogeneity plays a crucial role in the attainment of narrow FMR linewidths reflecting low magnetization damping of the films. Our findings shed new light on the estimation of the Gilbert damping parameter in epitaxial oxide layers that are envisioned for spintronic and magnonic applications.

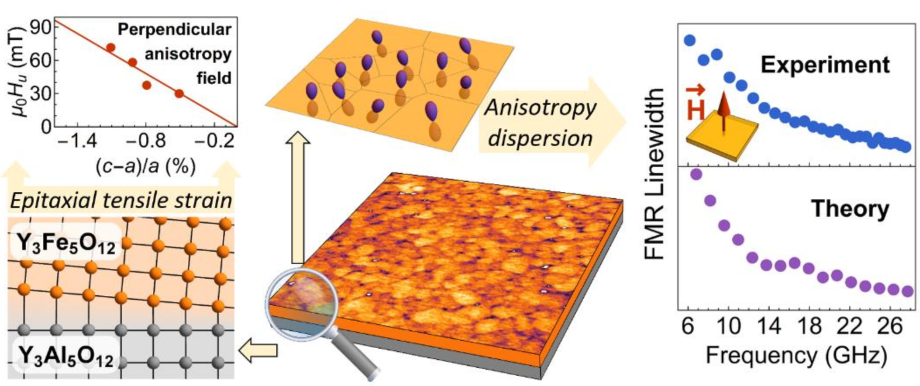

Figure 1: Interrelation between structural and magnetic properties in $Y_3Fe_5O_{12}$ / $Y_3Al_5O_{12}$.

[1] A. Krysztofik, S. Özoğlu, R. D. McMichael, E. Coy, Scientific Reports, 11:14011, 2021.

Transport properties and Spin Orbit Torque in single layers of Mn_2RuGa.

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Mn_2RuGa is a half metallic compensated ferrimagnet with perpendicular magnetic anisotropy that displays interesting properties for spintronics such as a low net magnetic moment and large anomalous Hall effect [1]. The XA structure ($F\bar{4}3m$) of the full Heusler lacks inversion symmetry and therefore allows for the possibility of spin orbit torque (SOT) originating from the bulk [2]. Other SOT contributions can arise from interfaces that, for any thin film sample, leads to ∞m symmetry with no inversion centre.

The SOT of Mn_2RuGa thin films was measured by harmonic Hall effect on patterned Hall bars where both the longitudinal and transverse voltages were recorded. Scans were performed with the field along the easy axis (z direction) and hard axis (xy plane). The magnetisation was modelled using a single macro-spin and tetragonal anisotropy. The first harmonic of both the longitudinal and transverse voltages can be explained by the Hall effect, the anomalous Hall effect, the planar Hall effect and magnetoresistance. They can be separated by scanning the field in different planes using a 2 T Multimag permanent magnet flux source. The second harmonic yields a combination of the purely-thermal Nernst effect, due to a temperature gradient in the z-direction, and the damping-like spin-orbit torque. The third harmonic reflects the uniform heating of the sample and any intrinsic contribution to the SOT arising from the absence of inversion symmetry. In Mn_2RuGa, the a and b axes are inequivalent, thanks to the tetrahedral symmetry of the central cube of Ru and Mn^{4c} atoms (Fig.1), and equal numbers of domains of the two variants are expected in thin films grown on cubic MgO.

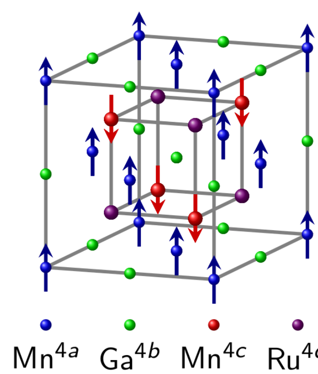

Figure 1: Crystal structure of Mn_2RuGa in the XA form, showing the lack of inversion symmetry.

The analysis illustrates that the non-linear second harmonic signal originates mainly from a combination of the interfacial SOT and Nernst effects. The third harmonic signal can be explained by Joule heating. Intrinsic SOT originating from the lack of inversion symmetry of the crystal was not expected to be observed in the second harmonics, on account of the two variants. In principle, it should be observable in the third harmonic because the perturbation has the same sign for the two variants. However, it was too small for us to detect because of the quasi-linear variation of M_z with applied field, which leads to a near-zero second derivative. We hope that we may detect the effect in much larger magnetic fields.

[1] K. E. Siewierska, G. Atcheson, *et al.*, *Phys. Rev. B*, vol. 104, 6 2021.

[2] J. Železný, H. Gao, *et al.*, *Phys. Rev. B*, vol. 95, 1 2017.

All-Optical Switchable Racetrack based on Compensated Co/Gd quadlayers

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Co/Gd based synthetic ferrimagnets have received considerable attention owing to the coexistence of both ultrafast all-optical switching (AOS) [1-2] and current driven domain wall motion (CIDWM) [3-4], allowing for novel, hybrid devices connecting spintronics with integrated photonics. So far, the velocity of CIDWM of Co/Gd is low due to large net magnetic moment.

Here, we experimentally demonstrate a fully layered based synthetic ferrimagnet Co/Gd(x)/Co/Gd quadlayer systems which shows simultaneously fast CIDWM and AOS. We first show the magnetic moment can be compensated at room temperature conditions(see inset of Fig. 1), where single pulse AOS is found to be present in the full range of Gd thickness[5]. The compensation can be seen by the reverse of Kerr contrast and divergence of the coercivity at the compensation thickness. From the wedge of the same batch, we carried out current induced domain wall velocity measurement and plotted the results in Fig. 1 (b). It can be observed that the domain wall velocity spikes at the thickness close angular momentum compensation. As the current density is increased the optimum in the velocity is found to shift towards larger Gd thicknesses, we attribute this to the difference in temperature dependence of the magnetization in Co and Gd leading to a shift in the compensation thickness due to joule heating. We further conducted numerical and theoretical modelling of the domain wall motion considering the Joule heating effect, a reasonable agreement with experiment was found [5].

Our study shows a significant improvement of the room temperature domain wall velocity in synthetic ferrimagnetic systems through stack engineering paving ways for hybrid integration of racetrack memory and AOS (with integrated photonics).

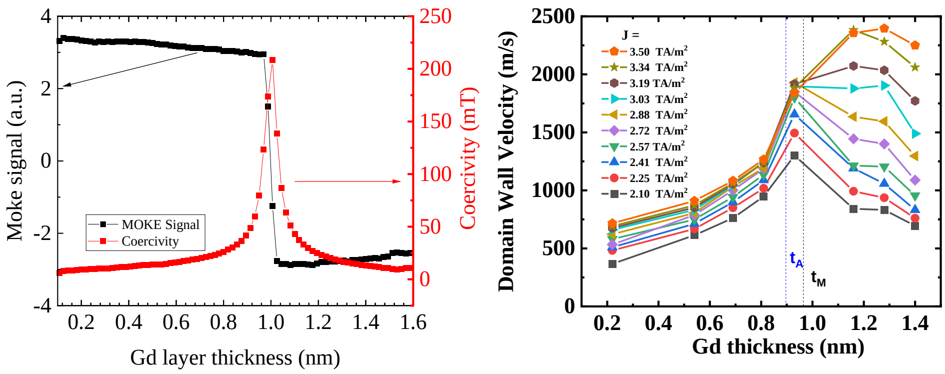
[1] : Lalieu, M.L.M., *et al. Physical Review B* 96.22 (2017): 220411.

[2] : van Hees, Youri LW, *et al. Nature communications* 11.1 (2020): 1-7.

[3] : Caretta, L. *et al. Nature Nanotechnology* 13.12(2018): 1748-3395

[4] : Blaesing, R. *et al. Nature Communications* 9.1(2018): 2041-1732

[5] : Li *et al. arXiv :2202.11595*



(a) **(b)**

Fig. 1: Coercivity, polar MOKE signal (a) and current-driven domain wall velocity (b) as a function of Gd thickness in a Si/SiO$_2$(100)//Ta(4)/Pt(4)/Co(0.6)/Gd(x)/Co(0.7)/Gd(1.5)/TaN(4) multilayer system, where the numbers between brackets denote layer thicknesses in nm, and the x indicates the wedged layer given on the x-axis. The dashed vertical line in (b) indicates the Gd thickness where angular momentum compensation is achieved (see(a)).

Poster title: THz emission spectroscopy of GdFeCo/Cu/Pt multilayers

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In recent years, THz spintronic emitters have emerged as intense, broadband radiation sources in this historically difficult-to-access frequency range. Through engineering of material properties and device architecture, researchers have optimized several aspects of these emitters. For instance, the incorporation of ferrimagnetic materials has resulted in the ability to tune the THz pulses through temperature and chemical concentration. At the same time, the study of these devices by THz emission spectroscopy provides a window into the magnetization dynamics and spin transport within their constituting materials.

In this work, we employed time-domain THz spectroscopy to characterize the THz emission from samples based on ferrimagnetic GdFeCo and Pt. By analyzing the symmetry of the generated THz pulses, we corroborated that their origin is the excitation of spin current due to the ultrafast demagnetization of GdFeCo, followed by spin-to-charge conversion in Pt through the inverse spin Hall effect. Moreover, temperature-dependent experiments displayed a strong decrease in the THz emission close to the magnetization compensation temperature (T_M) of the GdFeCo layer.

Previous research on ferrimagnetic THz spintronic emitters attributed the above-described behavior to the cancelation of the opposing rare earth and transition metal contributions to the THz signal [1] or to composition inhomogeneities in the sample [2]. Based on equilibrium magnetometry measurements and on the effect of a bias magnetic field on the THz pulses, we argue that the THz signal is suppressed close to T_M as a consequence of the out-of-plane magnetic anisotropy of the sample. This scenario is supported by a macro-spin model which is shown to reproduce the external field dependence of the experimental data.

Having concluded that the vanishing of the THz signal does not provide information regarding the relative magnitudes of the Gd and FeCo contributions, we address this outstanding issue by comparing the emission from samples with different Gd concentrations. The data hint that the rare earth contribution can be non-negligible, despite the localized character of the 4*f* electrons responsible for magnetism in Gd.

Our results constitute a systematic study of GdFeCo THz emitters and confirm the versatility of this alloy as a source of sub-picosecond spin current.

[1] T. Huisman, D. C. Ciccarelli, et al., Appl. Phys. Lett., vol. 110, no. 7, 2017.
[2] M. Chen, R. Mishra, et al., Adv. Opt. Mater., vol. 6, no. 17, 2018.

Magneto-ionic Reversibility in Annealed W/CoFeB/HfO_2

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Magneto-ionics (MI) is of great interest in spintronics primarily due to nonvolatile modulation of magnetic properties. However, the potential application of MI is restricted by lack of full reversibility and the switching speed. Several works have focused on with different types of ions, oxides, and degree of oxidation [1-3] to address these limitations, but the influence of annealing temperature on MI reversibility is still lacking in the literature. Annealing is is a common technique used to crystallize CoFeB to enhance perpendicular magnetic anisotropy (PMA), Dzyaloshinskii-Moriya interaction (DMI), and tunnel magnetoresistance [4-6]. Therefore, its impact on MI reversibility is of deep concern.

In this work, we study the influence of annealing on MI reversibility in W/CoFeB/HfO_2 where CoFeB is amorphous in the as-grown state. We observe that as-grown samples show in-plane magnetic anisotropy (IPA) and show no change with gate voltage, whereas samples annealed at 350°C and 390°C display PMA and transition to IPA with negative gate voltage. In addition, we show that 390°C annealing allows for higher DMI (0.6 mJ/m^2) and anisotropy, but is irreversible, whereas the 350°C annealing shows negligible DMI (0.06 mJ/m^2), lower anisotropy, and semi-reversibility of 60%.

This disparity in the degree of MI reversibility with different annealing profiles could be attributed to the degree of crystallization in CoFeB. As different annealing profiles change the size and distribution of CoFeB grains, it affects the ionic mobility inside the stack and therefore the reversibility. Our results show that annealing and phase of CoFeB has a strong impact on tuning between magnetic properties and reversibility and is of extreme importance for the design of MI based spintronics devices.

[1] Tan, et al., *Nat. Mater.* **18**, 35 (2019).
[2] Fassatoui, et al., *Phys. Rev. Appl.* **14**, 064041 (2020).
[3] Pachat, et al., *Phys. Rev. Appl.* **15**, 064055 (2021).
[4] Cho, et al., *IEEE Trans. on Magnetics* **54**, 15000104 (2018).
[5] Nagata, et al., *Appl. Phys. Lett.* **109**, 132404 (2016).
[6] Wang, et al., *Phys. Rev. B.* **81**, 144406 (2010).

Using Propagating Spin Wave Spectroscopy to Probe Interfacial Phenomena Modified by an Electric Field

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Electric field-controlled data storage and logic devices promise an energy consumption up to a hundred times less compared to current state-of-the-art [1]. Although the effect of an electric field on the Magnetic Anisotropy (MA) [2] and interfacial Dzyaloshinskii-Moriya (iDMI) [3] has been reported, no measurement technique is available that can untangle the intricate effect of an electric field simultaneously. In this project, we aim to adapt a technique relying on propagating spin wave spectroscopy [4] to probe all these electric field-induced effects of interfacial magnetic properties, self-consistently.

In this presentation, I will present our latest simulations and experimental results aiming at proving the self-consistency, backed up with conventional techniques. We study the influence of the electric field strength as well as the width of the electric gate (E-gate) (see Fig. 1a) on the transmission of the spin waves through the region where the magnetic properties are locally modulated. Here we localized an electric field at the interface between an insulator (MgO) and the spin-wave guiding ferromagnet (Co), which changes the electronic band-structure and hence is expected to give rise to small changes in the interfacial properties e.g. the MA and the iDMI. As can be seen in Fig. 1b, simulations show a change of amplitude of the transmitted forward volume spin wave once it has travelled through a region where the anisotropy (H_{Anis}) is locally modified by an electric field (H_{Efield}).

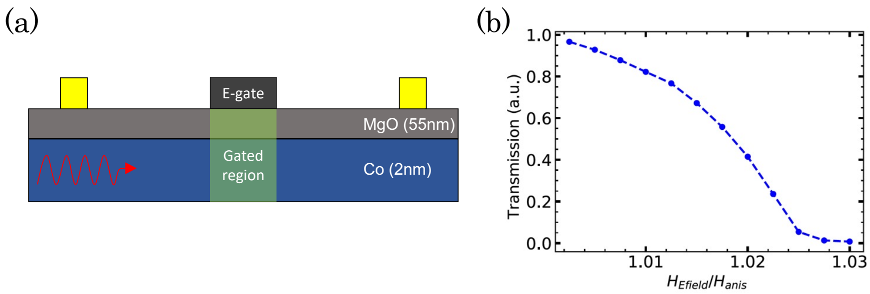

Figure 1: (a) A spin wave (red) is created by the antenna on the left (yellow) and propagates through the gated region (green) before being detected by the antenna on the right. (b) Transmission of a forward volume mode as a function of the relative strength of the anisotropy modified by the electric field in the gated region. Spin wave frequency is 5GHz and Gated region width is 800nm.

Ultimately, as the changes induced by an electric field on MA and iDMI can be small, we hope to provide the scientific community with a technique relying on the propagation of spin waves to probe the smallest change of interfacial magnetic properties, induced by an electric field. Moreover, the wave nature of spin wave and the possibility to control their dispersion relation by locally applying an electric field, could lead to the conception of novel spin-wave based logic devices, contributing to green IT.

[1] F. Matsukura, Y. Tokura and H. Ohno, *Nat. Nanotechnol.* **10**, 209-220 (2015).
[2] Z. Huang *et al.*, *Appl. Phys. Lett.* **103**, 222902 (2013).
[3] T. Strivastava *et al.*, *Phys. Nano. Lett.* **18**, 4871-4877 (2018).
[4] J. Lucassen *et al.*, *Phys. Rev. B.* **101**, 064432 (2020).

Gauge theory applied to magnetic lattices

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Micromagnetism [1] is at the core of modern computational efforts that try to capture the statics and dynamics of macroscopic magnetic bodies. Micromagnetic exchange is traditionally derived by performing the continumm limit of the Heisenberg Hamiltonian on a cubic lattice where the exchange integrals are assumed to be identical for all nearest neighbors. These limitations normally impose the use of a microscopic theory to account for the appearance of higher order magnetic interactions such as DMI [2], [3]. In this paper we combine graph theory and gauge field theory to simultaneously account for the symmetry properties of the crystal, the effect of spin-orbit coupling and their interplay on a micromagnetic level that does not require us to work on an atomic scale. The outcome is going to be a theory that allows to derive the continuum limit of micromagnetic interactions accounting for the crystal symmetries at all orders in exchange. As an example, we are going to show how this method can successfully predict the form of micromagnetic DMI in all 32 crystallographic point groups and discuss the consequences of different DMI tensor components.

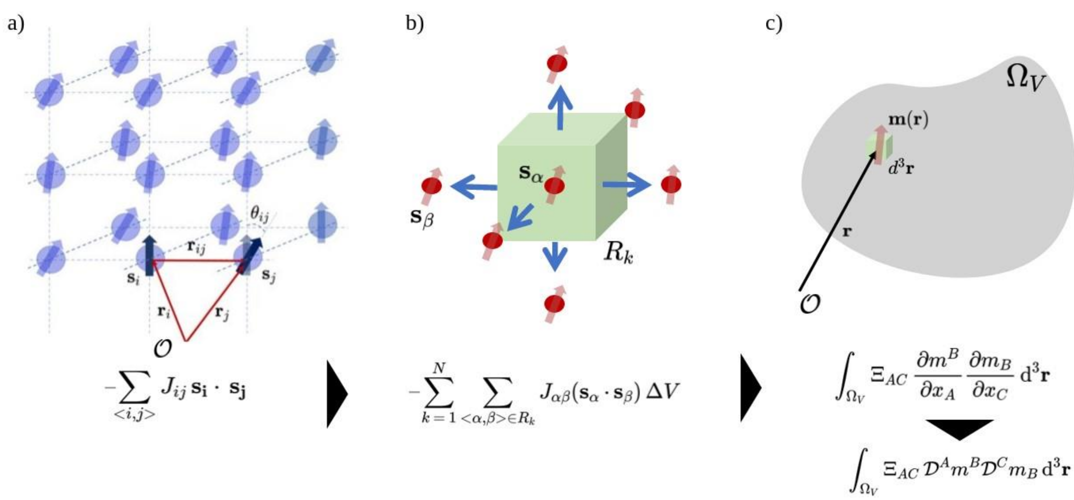

Figure 1: a) Heisenberg model on a cubic lattice. b) Decomposition of the cubic lattice in nearest neighbour clusters using the Voronoi tassellation. c) Continuum limit performed on the cell from b). The Gauge covariant derivative is introduced in the last step.

[1] W. Brown. 1963.

[2] T. Moriya, *Phys. Rev.*, vol. 120, no. 1, 1960.

[3] I Dzyaloshinsky, *J. Phys. Chem. Solids*, vol. 4, no. 4, 1958.

In plane magnetic field dependence of anomalous Hall conductivity in a non-collinear antiferromagnet

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Non-collinear antiferromagnets (NC-AFM) have attracted much attention recently due to the observation of the anomalous Hall effect (AHE) in these materials [1,2,3] despite the small magnetic moments present in their unconventional spin structures. These materials have also exhibited an anomalous Nernst effect which is possible to manipulate with strain [4]. These fascinating qualities have deep rooted connections with the magnetic octupole moment [5] that could be harnessed to enable chirality switching [6] and bring these materials ever closer to realistic AFM spintronic devices.

Here we study the AHE as a function of magnetic field direction in the Kagome (111) plane of the antiperovskite nitride $Mn_3Ni_{0.35}Cu_{0.65}N$. We explain the resulting magnetic field orientation dependence of the AHE in the context of irreducible representations of the three-spin primitive unit cell, showing a deeply connected interplay between magnetic field dependence of AHE and the octupole moment by fitting to density functional theory calculations. Further, we present non-trivial features in the magnetic field dependent AHE loops before the onset of saturation signifying additional stable spin configurations, and potentially novel transport phenomena. These results open the possibility of a lever through which the spin structure in NC-AFMs can be manipulated making $Mn_3Ni_XCu_{1-X}N$, and more generally antiperovskite nitrides, another class of materials which shows genuine promise in realizing a more efficient memory device concept.

[1] H. Chen, Q. Niu, and A. H. MacDonald, *Anomalous Hall Effect Arising from Noncollinear Antiferromagnetism*, Phys. Rev. Lett. **112**, 017205 (2014).

[2] S. Nakatsuji, N. Kiyohara, and T. Higo, *Large Anomalous Hall Effect in a Non-Collinear Antiferromagnet at Room Temperature*, Nature **527**, 212 (2015).

[3] K. Zhao, T. Hajiri, H. Chen, R. Miki, H. Asano, and P. Gegenwart, *Anomalous Hall Effect in the Noncollinear Antiferromagnetic Antiperovskite Mn 3 Ni 1 − x Cu x N*, Phys. Rev. B **100**, 045109 (2019).

[4] F. Johnson, J. Kimák, and J. Zemen, *Identifying the Octupole Antiferromagnetic Domain Orientation in Mn3NiN by Scanning Anomalous Nernst Effect Microscopy*, Applied Physics Letters **120**, 232402 (2022).

[5] M.-T. Suzuki, T. Koretsune, M. Ochi, and R. Arita, *Cluster Multipole Theory for Anomalous Hall Effect in Antiferromagnets*, Phys. Rev. B **95**, 094406 (2017).

[6] D. Go, M. Sallermann, F. R. Lux, S. Blügel, O. Gomonay, and Y. Mokrousov, *Non-Collinear Spin Current for Switching of Chiral Magnetic Textures*, Phys. Rev. Lett. **129**, 097204 (2022).

Exploring multiple strain geometries in PMN-PT/Ta/CoFeB/MgO magneto-electric devices

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Strain-induced modification of magnetic properties in hybrid piezoelectric/ferromagnetic heterostructures is being intensively investigated due to its potential for low power spintronics applications based on magnetic domain wall (DW) motion ([1], [2]).
In this study, we present PMN-PT (011)/Ta/CoFeB/MgO based devices where both out-of-plane and in-plane strain configurations have been exploited to control DW dynamics. In PMN-PT (011), the application of a gate voltage along the out-of-plane (OOP) direction of the sample leads to a non-volatile polarisation state which can be reverted back to the un-poled state by annealing at temperatures above the Curie temperature ([3]), which was confirmed in our system by piezoresponse force microscopy. In this configuration we observe a non-volatile increase in the coercivity in 10µm wires in the poled state of about 90% with respect to the unpoled state. This response can be linked not only to a strain-control of magnetic anisotropy but also to a strain-controlled change in the homogeneity of the magnetic landscape. The multiple polarisation directions of the domains in the un-poled state of the PMN-PT can translate into a wider anisotropy distribution in the magnetic system, compared to the poled state. This can significantly affect DW nucleation/depinning fields, which opens the door to using strain to control magnetic disorder. We also combine this non-volatile effect with local, volatile, in-plane control of DW dynamics, dominated by strain-induced changes in magnetic anisotropy.
In conclusion, we present a multifunctional strain-controlled device where both disorder and anisotropy can be manipulated. We show that multiple strain configurations in piezoelectric/ferromagnetic hybrid structures can open new opportunities for the electrical manipulation of DW dynamics.

References

[1] Na Lei et al. *Nature Communications*, 4:1–4, 2013.

[2] P. M. Shepley et al. *Scientific Reports*, 5:1–5, 2015.

[3] V.S. Kathavate al. *Ceramics International*, 46(8, Part B):12876–12883, 2020.

Superparamagnetic tunnel junctions for neuromorphic computing

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Superparamagnetic tunnel junctions (SMTJ) are promising candidates for the implementation of neuromorphic computing. In a SMTJ, the magnetic free layer can switch its orientation induced by thermal activation, leading to a random two-level resistance fluctuation with relaxation times in the order of a few nanoseconds [1]. Their intrinsic stochastic behaviour and additional tunability by external magnetic fields, Spin Transfer Torques (STT) or Spin Orbit Torques (SOT) are key ingredients for low-energy artificial neurons in neural networks. Non-conventional computing, like inverse logic for integer factorization already has been demonstrated based on SMTJs [2]. Measurements of the characteristic stochastic switching behaviour are highlighted and the quality of randomness (according to NIST Statistical Test Suite) for a SMTJ as a potential true random number generator is evaluated. New possible implementation ideas of a stochastic neural network based on SMTJs are proposed and their efficiency is studied in detail.

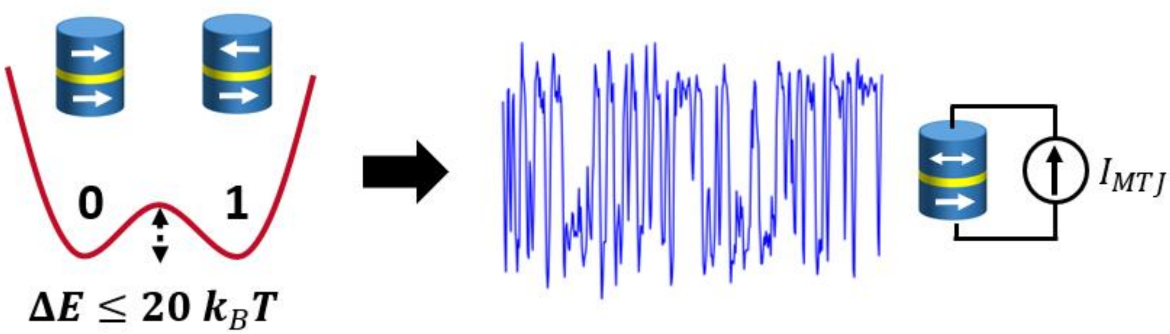

Figure 1: In a superparamagnetic tunnel junction (SMTJ), thermal excitations can lead to a switching of the free layer magnetization resulting in stochastic resistance fluctuations between the parallel and the anti-parallel state of the MTJ.

[1] Hayakawa, K. et al., Phys. Rev. Lett. 126, 117202 (2021)
[2] Borders, W. A. et al., Nature 573, 390-393 (2019).

Analysis of Exchange Bias training effect in Exchange coupled $LaFeO_3$ /NiO nanocomposite

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ABSTRACT

Existence of exchange bias (EB) resulting from antiferromagnetic/ferromagnetic interface is well known in the literature [1]. EB phenomenon is characterized by the horizontal shift of the magnetic hysteresis loop as the system is cooled through Neel's temperature in presence of an external magnetic field. In addition, a simultaneous hysteresis loop shift along the magnetization axis has also been observed frequently in the literature and is termed as "vertical magnetization shift" (VMS). EB is the backbone of designing magnetic storage devices and is among the modern approaches to spintronics. One of the interesting characteristics of EB is the training effect [2]. In this work, we investigate the exchange bias training effect (TE) in $LaFeO_3$/NiO nanocomposite synthesized by a complex propylene glycol gel chemical route. The consecutive measurement of field cooled (60 kOe) magnetic hysteresis loops at 5 K show that the exchange bias field (H_E) decreases with the increasing number of cycles of M-H loops (n) confirming the presence of the TE effect in our sample (see Fig 1(a)). The experimentally observed trend between H_E and n was fitted using the general power law and Binek's recursive relation (see Fig 1(b)). The fitting parameter obtained from the power law is $H_{E(\infty)} = 1253$ Oe; where $H_{E(\infty)}$is the magnitude of the exchange bias field in the limit of infinite loops. From the Binek's recursive relation, the obtained value of $H_{E(\infty)}$ and γ (sample dependent constant) is 1118 Oe & 6.9×10^{-7} $(Oe)^{-2}$, respectively. Both, the power law and Binek's recursive relation points coincide well with the experimental observations.

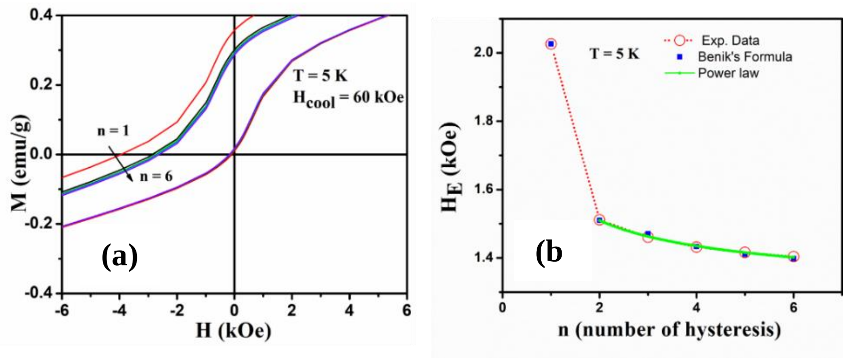

Figure 1 (a) Enlarged view of six consecutive M-H loop cycles in cooling field of 60 kOe measured at 5 K, (b) solid squares represents the data points calculated by using Binek's recursive relation, solid line corresponds to Power law fitted data and experimental data is represented by using the circular symbol.

References:

[1] M. Kiwi, Exchange bias theory, Journal of Magnetism and Magnetic Materials, 234 (2001) 584-595.

[2] C. Binek, Physical Review B 70 (1), 014421 (2004).

Enhanced domain wall motion by dynamic strain induced by surface acoustic waves

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The effect of the travelling surface acoustic wave (SAW) induced dynamic strain on domain wall (DW) motion and DW structure in Pt/Co/Ta thin films with perpendicular magnetic anisotropy has been investigated both experimentally and numerically. Two-millimetre wide Pt/Co(t)/Ta thin films (t=0.7 or 0.9 nm) have been deposited using magnetron sputtering. Interdigitated transducers, which can generate SAWs with centre frequencies of 50, 100 and 200 MHz, were fabricated by the two ends of thin films. DW motion and its velocity were observed and measured using Kerr Microscope. Results showed that DW motion is within the creep regime for all studied cases. The DW velocity decreases as the SAW frequency increases in the thin film with the thinner Co layer. On the contrary, DW velocity increases with the increasing SAW frequency. Micromagnetic simulations were performed by Mumax3 to understand the SAW frequency effect on the DW motion. Simulation results showed a good agreement with the experimental results revealing that SAW introduces spin rotation in the DW following the SAW frequency. The SAW-induced spin rotation, on the one hand, enhances the possibility of the domain depinning from the pinning sites; on the other hand, also causes energy wastage. Which factor plays the main role depends on the depinning energy and SAW frequency.

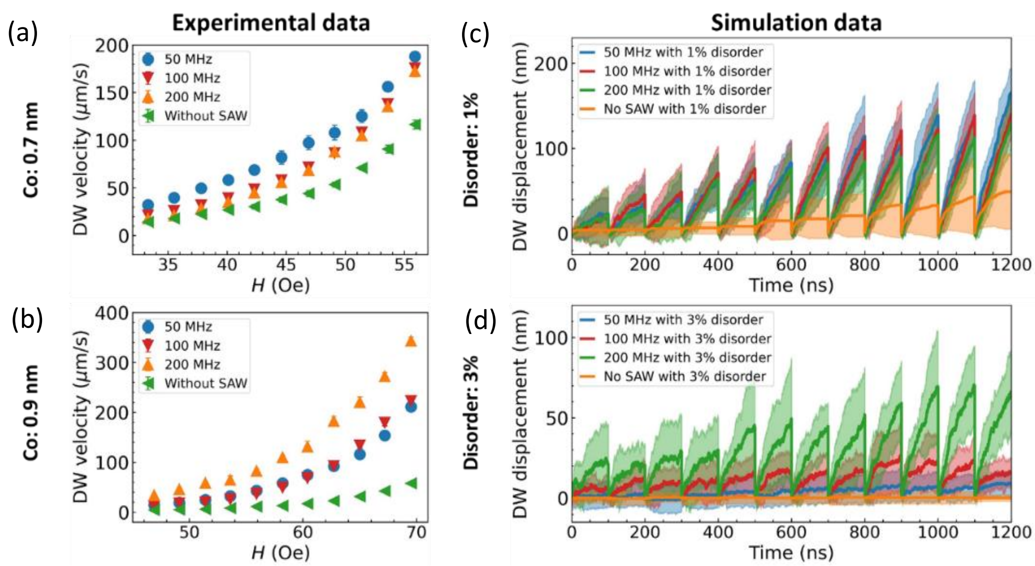

Figure 1: Experimental results of the domain wall velocity against field in Pt/Co/Ta thin films with (a) 0.7 nm Co and (b) 0.9 nm under different SAW frequencies. Simulation results of the domain wall displacement against time with (c) 1% and (d) 3% anisotropy disorder.

[1] Marathe et al. Vacuum, 14, 329, (2017)
[2] Li et al., J. Appl. Phys, 115, 17E307 (2014)
[3] Shepley Sci. Rep. 5, 7921 (2015)
[4] Shuai et al. Appl. Phys. Lett. 120, 252402 (2022)