Early Career Researchers' Presentations and Networking
EPSRC International Network for Spintronics
From Material Development to Novel Energy Efficient Technologies

~ Times shown are in BST (+1h for CEST, +8h for JST and –5h for EDT) ~

Zoom link to be provided by e-mail to registered participants

Invited talks: 25 min. presentation + 5 min. discussion
Contributed talks: 13 min. presentation + 2 min. discussion

Thursday, 19 May

07:50 (08:50/15:50)	Welcome
08:00~10:00 (09:00~11:00/ 16:00~18:00)	Session 1: Magnonics and Magneto-Optical Effects *Chair: Miina Leiviskä (Spintec)*
08:00 (09:00/16:00)	Matthias Schweizer (*TU Kaiserslautern*) "Magnon condensation in thermal landscapes"
08:15 (09:15/16:15)	David Breitbach (*TU Kaiserslautern*) "Amplification of spin waves by rapid cooling"
08:30 (09:30/16:30)	David Salomini (*Spintec*) "Ultrafast opto-magneto-spintronics"
08:45 (09:45/16:45)	Daiki Sekine (*Tohoku Univ.*) "Direct detection of mesoscopic magnetic toroidal moment by optical second harmonic generation"
09:00 (10:00/17:00)	Anulekha De (*TU Kaiserslautern*) "Observation of terahertz frequency perpendicular standing spin wave modes in ultrathin permalloy films"
09:15 (10:15/17:15)	Charlotte Bull (*Univ. of Manchester*) "Spintronic terahertz emitters: impact of structural and magnetic properties"
09:30 (10:30/17:30)	Eva Prinz (*TU Kaiserslautern*) "Does the orbital angular momentum of light affect ultrafast demagnetization?"
09:45 (10:45/17:45)	Ivan vera Marun (*Univ. of Manchester*) "Update on graphene spintronics"
10:00 (11:00/18:00)	Break
10:15~12:45 (11:15~13:45/ 18:15~20:45)	Session 2: Antiferromagnetic Spintronics and Interfaces *Chair: Hiroto Masuda (Tohoku Univ.)*
10:15 (11:15/18:15)	Tom Thomson (*Univ. of Manchester*) "Overview of spintronics in Manchester"
10:45 (11:45/18:45)	Razan Aboljadayel (*Univ. of Leeds*) "Synthetic antiferromagnetic skyrmions"
11:00 (12:00/19:00)	Will Griggs (*Univ. of Manchester*) "Polarised neutron reflectometry characterisation of interfacial magnetism in an FePt/FeRh exchange spring"
11:15 (12:15/19:15)	Christoforos Moutafis (*Univ. of Manchester*) "Magnetic skyrmions for nanocomputing"
11:30 (12:30/19:30)	Thomas Nussle (*Univ. of Leeds*) "Magnetoelasticity: Using strain to control magnetic switching in antiferromagnets"
11:45 (12:45/19:45)	Shoma Akamatsu (*Tohoku Univ.*) "Guidelines for attaining optimal soft magnetic properties in FeAlSi films"
12:00 (13:00/20:00)	David Lloyd (*Univ. of York*) "Structural investigation of CoIrMnAl Heusler

	alloy epitaxial films for spintronics applications"
12:15 (13:15/20:15)	Moritz Winter (*IFW Dresden*) "Magnetic imaging of antiskyrmions in $Mn_{1.4}PtSn$ using Lorentz TEM and electron holography"
12:30 (13:30/20:30)	Robert Lawrence (*Univ. of York*) "Atomistic control of magnetic anisotropy"
12:45 (13:45/20:45)	Photograph – Screenshot & Networking
13:00 (14:00/21:00)	Close

Friday, 20 May

08:00~10:00 (09:00~11:00/ 16:00~18:00)	Session 3: 2D spintronics *Chair: Misbah Yaqoob (TU Kaiserslautern)*
08:00 (09:00/16:00)	Matthew Rogers (*Univ. of Leeds*) "Towards molecular interface spintronics"
08:15 (09:15/16:15)	David Perkins (*Univ. of York*) "Twist-angle control of collinear Edelstein effect in van der Waals heterostructures"
08:30 (09:30/16:30)	Toby Bird (*Univ. of York*) "Gas phase synthesis of magnetic core-shell nanoparticles"
08:45 (09:45/16:45)	Chuang Chien-Wen (*Tohoku Univ.*) "Spectroscopy study of ferromagnetic topological insulator"
09:00 (10:00/17:00)	Ahmet Yagmur (*Univ. of Leeds*) "Towards functional topological insulator films"
09:15 (10:15/17:15)	Gabriele Bertolini (*Univ. of York*) "The field-emission regime of scanning tunneling microscopy for spintronic materials"
09:30 (10:30/17:30)	Fatima Ibrahim (*Spintec*) "Spin-orbit induced phenomena at ferromagnet/oxide and ferromagnet/2D material interfaces from first principles"
09:45 (10:45/17:45)	Harry Waring (*Univ. of Manchester*) "Exchange constant determination using multiple-mode FMR perpendicular standing spin waves"
10:00 (11:00/ 18:00)	Break
10:15~12:15 (11:15~13:15/ 18:15~20:15)	Session 4: 3D spintronics and Magnetic Skyrmions *Chair: David Lloyd (Univ. of York)*
10:15 (11:15/18:15)	Olivier Fruchart (*Spintec*) "3D spintronics"
10:45 (11:45/18:45)	Takaaki Dohi (*Johannes Gutenberg Univ. of Mainz*) "Dynamics of antiferromagnetically coupled skyrmions in synthetic antiferromagnet"
11:00 (12:00/19:00)	Miina Leiviskä (*Spintec*) "Atomistic simulations on imprinting of skyrmion textures from a ferromagnet to an antiferromagnet"
11:15 (12:15/19:15)	Takumi Yamazaki (*Tohoku Univ.*) "Optical thermometry for investigating spin caloritronics"
11:30 (12:30/19:30)	Hassan Al-Hamdo (*TU Kaiserslautern*) "Magnetization dynamics in thin film $Mn_2Au/Ni_{80}Fe_{20}$ bilayers"
11:45 (12:45/19:45)	Misbah Yaqoob (*TU Kaiserslautern*) "Spin-orbit torques in ferromagnetic heterostructures"
12:00 (13:00/20:00)	Philippa Shepley (*Univ. of Leeds*) 'Thin films from the Royce deposition system"
12:15 (13:15/ 20:15)	Networking
12:30 (13:30/20:30)	Close

Magnon condensation in thermal landscapes

Matthias Schweizer [1]

[1] *TU Kaiserslautern*

Amplification of spin waves by rapid cooling

David Breitbach [1]

[1] *TU Kaiserslautern*

Ultrafast opto-magneto-spintronics

David Salomini [1]

[1] *Spintec*

Direct detection of mesoscopic magnetic toroidal moment by optical second harmonic generation

Daiki Sekine,[1] Yoshifumi Sato [1] and Masakazu Matsubara [1, 2]

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Recently, magnetic orders without space inversion and time reversal symmetries have attracted much attention because they induce magnetoelectric (ME) phenomena and nonreciprocal propagation of light [1]. Magnetic toroidal (MT) moment ($\boldsymbol{T}$), which is defined as a cross product of position vectors ($\boldsymbol{r}_i$) and magnetic moments ($\boldsymbol{m}_i$) (Fig. 1(a)), is one of the ME-acitve orders and is regarded as the origin of linear ME effect [2]. Since the MT moment has no net magnetization, however, it is difficult to directly detect it by conventional techniques. In this study we performed optical second harmonic generation (SHG) measurements to detect the MT moment. SHG, which is one of the second-order nonlinear optical effects, is sensitive to breaking of both space inversion and time reversal symmetries. Therefore, SHG can be an ideal probe to detect the MT moment.

We fabricated triangular-shaped permalloy ($Ni_{78}Fe_{22}$) nanomagnets on SiO_2 substrate by an electron beam lithography (Fig. 1(b)). We confirmed by micromagnetic simulation that the MT moment can be controlled by external magnetic fields and there is no net magnetization at zero fields (Fig. 1(c)). Therefore, this can be a model system of the mesoscopic MT moment.

Fig. 1(d) shows the result of magnetic field dependence of the SHG intensity in increasing and decreasing runs. The qualitative behavior of magnetic field dependence of the SHG intensity agrees with the result of micromagnetic simulation. The difference in the SHG intensity around 0 mT comes from the opposite direction of the MT moment. This indicates that SHG can directly detect MT moment and its direction [3]. This technique can be applied to other ME-active orders, like magnetic monopoles and magnetic quadrupoles.

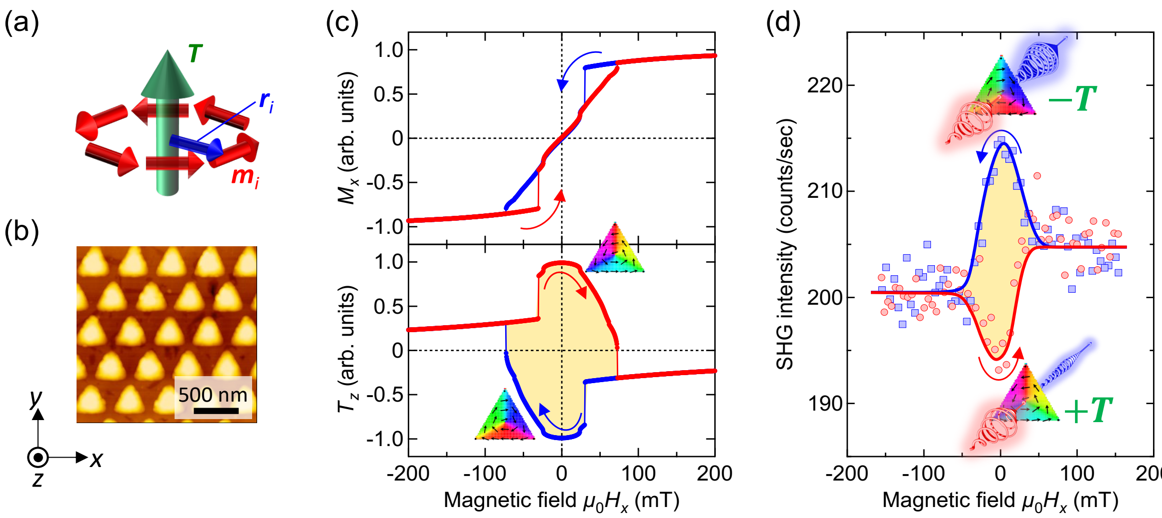

Fig. 1 (a) Schematic image of MT moment. (b) Atomic force microscope image of triangular-shaped nanomagnets. (c) Magnetic field dependence of magnetization ($\boldsymbol{M}_x$) and MT moment ($\boldsymbol{T}_z$) estimated by micromagnetic simulation. (d) Magnetic field dependence of the SHG intensity.

References:
[1] Y. Tokura and N. Nagaosa, *Nat. Commun.* **9**, 3740 (2018).
[2] C. Ederer and N. A. Spaldin, *Phys. Rev. B* **76**, 214404 (2007).
[3] D. Sekine, Y. Sato and M. Matsubara, *Appl. Phys. Lett.* **120**, 162905 (2022).

Observation of terahertz frequency perpendicular standing spin wave modes in ultrathin permalloy films

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High frequency spin-wave (SW) dynamics driven by ultrashort laser pulses have been studied in a wide range of ferromagnetic thin films and multilayers over the past few decades. One of the most thoroughly explored SW modes in ferromagnetic films is the perpendicular standing spin wave (PSSW). Regarding metallic ferromagnetic layers, $Ni_{80}Fe_{20}$ (permalloy, Py) is a model system for the study of PSSW states, either in single layers [1], or in films coupled to adjacent ferromagnetic [2], or antiferromagnetic layers [3]. In general, the formation of PSSWs requires either nonuniform excitation or pinning of the magnetization. We investigate PSSW modes in ultrathin Py films by means of an all-optical, time-resolved magneto-optical Kerr effect (TR-MOKE) technique based on a two color non-collinear pump-probe set up [4]. An amplified Ti:Sapphire laser system (800 nm, 35 fs, 1 kHz) is used to generate the pump and probe beams. The original 800 nm beam of the laser is used as the pump beam and the second harmonic beam (400 nm) is used as the probe beam. The TR-MOKE experiments are performed in polar geometry with a magnetic field applied in a direction slightly canted (~ 15°) from the plane of the sample. The Py films with thicknesses of 2.8 and 5 nm are deposited on a MgO substrate by molecular beam epitaxy (MBE). After ultrashort optical excitation, ferromagnetic resonance (FMR) modes in the gigahertz (GHz) frequency range are excited caused by the slightly canted external magnetic field. These FMR modes decay into the PSSW modes in the terahertz (THz) frequency regime within few tens of ps. The frequencies of the exchange coupled PSSW modes change drastically with the change of the film thickness. We observed the 1st order PSSW modes at 1 THz and 0.5 THz for 2.8 nm and 5 nm Py films, respectively. The peak intensities of the transiently excited PSSW modes gradually increase with time, reach a maximum, and decay on larger time scales. This study will stimulate further investigation of the THz magnon coupling and pave the way toward THz spintronics.

Acknowledgements: This study was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through No. TRR 173–268565370 (project B11).

References:

[1] Y. V. Khivintsev *et al.*, *J. Appl. Phys.* **108**, 023907 (2010).
[2] D. C. Crew *et al.*, *J. Appl. Phys.* **97**, 10A707 (2005).
[3] R. Magaraggia *et al.*, *Phys. Rev. B* **83**, 054405 (2011).
[4] M. Stiehl *et al.*, *Appl. Phys. Lett.* **120**, 062410 (2022).

Spintronic terahertz emitters: impact of structural and magnetic properties

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[2] *Department of Physics & Astronomy & Photon Science Institute, University of Manchester, United Kingdom*

The ability to generate and control pulses of terahertz (THz) radiation has mediated the advance of non-invasive, investigative technologies for material characterization, medical diagnosis and weapon detection [1]. Pulses of THz radiation have potential applications in ultrafast control of electron spin states [2] and picosecond magnetization switching in ferrimagnets and antiferromagnets [3]. Such applications require sources that generate THz pulses with high electric field amplitudes, broad spectral bandwidths and gapless coverage over the full THz spectral region (1-10 THz) [1]. Spintronic emitters, consisting of ferromagnetic (FM)/non-magnetic (NM) thin films, can produce THz pulses with gapless bandwidths of up to 30 THz [4]. In these systems, high THz electric field amplitudes, E_{THz}, of up to 300 kV/cm [4] can be achieved by combining appropriate FM and NM materials and by choosing a NM material with a large spin-Hall angle, such as Pt [1]. Furthermore, E_{THz} has been shown to scale with the magnetic moment of the FM layer, to which the THz pulses are perpendicularly polarized [1]. This offers a unique possibility to create devices in which the THz amplitude and polarization can be controlled through magnetic manipulation [5].

One aspect of our research focusses on exploring this potential, where we have exploited uniaxial magnetic anisotropy (UMA) in $Co_{20}Fe_{60}B_{20}$ (2.5 nm)/Pt (2 nm) bilayers to achieve polarization controlled THz emission, without the need for mechanical rotation of external magnets (Fig. 1) [6]. Other research investigates the role that material properties contribute to the THz generation process, where we have explored the effect of Cu doping on the emission of THz radiation from $Co_{20}Fe_{60}B_{20}$ (2.5 nm)/$Pt_{1-x}Cu_x$ (2 nm) bilayers ($0 \le x \le 80$ at %). Cu doping has been shown to increase the spin Hall efficiency of Pt by 29% [7], thus providing a potential to increase the amplitude of the emitted THz pulse through engineering of the Pt layer.

The emitters for these studies were fabricated by DC magnetron sputtering ($Co_{20}Fe_{60}B_{20}$) and co-sputtering (Pt and Cu). Structural properties were measured using X-ray photon spectroscopy providing elemental composition, X-ray diffraction and X-ray reflectivity, providing depth-dependent structural profiles. Terahertz time-domain spectroscopy was used to measure the amplitude of E_{THz} at saturation ($H_{app} > M_s$), at remanence ($H_{app} = 0$), and to measure the THz hysteresis behavior with varying H_{app}. The corresponding magnetic properties, obtained by vibrating sample magnetometry, are well-matched to the THz results. We observe a 15% increase in the THz emission amplitude of CoFeB/$Pt_{1-x}Cu_x$ bilayers with Cu doping (Fig. 2), and demonstrate that CoFeB/Pt bilayers with strong UMA can act as field-free emitters, remaining stable under continuous laser pumping [6]. These findings are key for the development of high performance and zero-field applications.

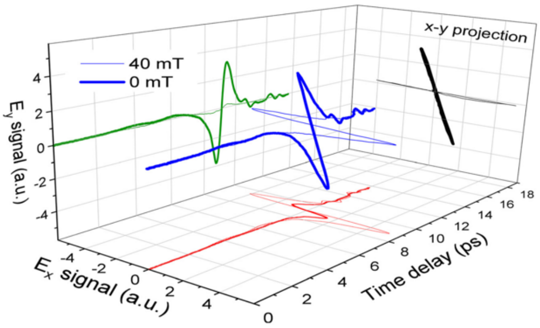

Fig. 1: Field manipulated polarization control of THz emission from CoFeB (2.5 nm)/Pt (2 nm) bilayers, exhibiting strong UMA.

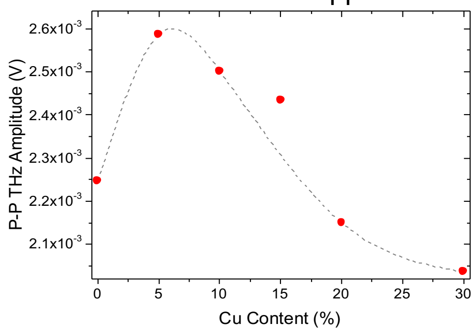

Fig. 2: Peak-peak THz emission amplitude measured from CoFeB (2.5 nm)/$Pt_{1-x}Cu_x$ (3 nm) bilayers with increasing Cu content.

Acknowledgements: This work is supported by the United Kingdom Engineering and Physical Sciences Research Council (Grant No. EP/S033688/1).

References: [1] Bull *et al.*, *APL Mater.* **9**, 090701 (2021). [2] Baierl *et al.*, *Nat. Photon.* **10**, 715 (2016). [3] Wienholdt *et al., Phys. Rev. Lett.* **108**, 247207 (2012). [4] Seifert *et al., Nat. Photon.* **10**, 483 (2016). [5] Hibberd *et al.*, *Appl. Phys. Lett.* **114**, 031101 (2019). [6] Hewett *et al., Appl. Phys. Lett.* **120**, 122401 (2022). [7] G. Wong *et al.*, *Sci. Rep.* **10**, 9631 (2020).

Does the orbital angular momentum of light affect ultrafast demagnetization?

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Optical fields can carry an orbital angular momentum (OAM) of $L = l\hbar$ with the OAM quantum number $l \in \mathbb{Z}$. Since its discovery in 1992 [1], there has been a variety of applications of light with additional OAM, such as quantum entanglement, micromanipulation, communication, and microscopy [2].

Our research focuses on exploring the potential impact of the OAM of light on laser-induced ultrafast demagnetization of ferromagnetic materials. In this field, the question of how the angular momentum is conserved during the optically induced loss of magnetic order has not yet been fully answered. It has been shown that the spin angular momentum of light does not affect ultrafast demagnetization in ferromagnetic thin films such as Ni [3, 4]. However, pumping such a system with photons carrying OAM offers the potential to provide new insights, not only into the dissipation of angular momentum in the material but also into the interaction of optical OAM with matter in general.

We investigate ultrafast demagnetization of ferromagnetic thin films induced by OAM light with time-resolved magneto-optic Kerr-effect measurements. We observed peculiar demagnetization dynamics that have so far not been observed for light without OAM.

References:

[1] L. Allen *et al*., *Phys. Rev. A* **45**, 8185 (1992).
[2] Y. Shen *et al*., *Light: Sci. Appl.* **8**, 1 (2019).
[3] B. Koopmans *et al*., *Phys. Rev. Lett.* **85**, 844 (2000).
[4] F. Dalla-Longa *et al*., *Phys. Rev. B* **75**, 224431 (2007).

Update on graphene spintronics

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Spintronic devices hold the promise of enabling energy-efficient information storage and logic operation applications. To achieve this, spins need to undergo injection, transport, and manipulation in a channel. Two-dimensional (2D) materials, including graphene, serve as a prototypical platform to explore this basic physics and to develop novel device architectures [1].

Here we will provide an update of recent research at the University of Manchester on novel device architectures for graphene-based spintronics, as well as comment on ongoing work. First, we will address the achievement of efficient spin injection in graphene via ultra-thin tunnel barriers, enabled by graphene functionalized with phenyl radicals which introduce sp^3 bonding in the graphene lattice. The functionalization is achieved by using a laser beam to catalyse a photochemical reaction with sub-micron spatial resolution. Atomic force microscopy demonstrates smooth ultrathin tunnel barriers which lead to an increased efficiency in spin injection [2].

Next, we will report on a spintronic device architecture consisting of fully encapsulated graphene contacted via one-dimensional (1D) ferromagnetic contacts (Fig. 1). Encapsulation in hexagonal boron nitride preserves the high quality of the graphene channel, resulting in long range charge and spin transport [3]. In line with previous works [4,5], the 1D contacts mitigate many of the issues associated with 2D tunnel contacts. Importantly, the geometry of the contact places transport in the ballistic regime. The latter enables sizeable contact resistance without the need for tunnel barriers and opens the possibility of studying novel phenomena, such as tuneable spin injection and quantized conductance in magnet/graphene spin injector.

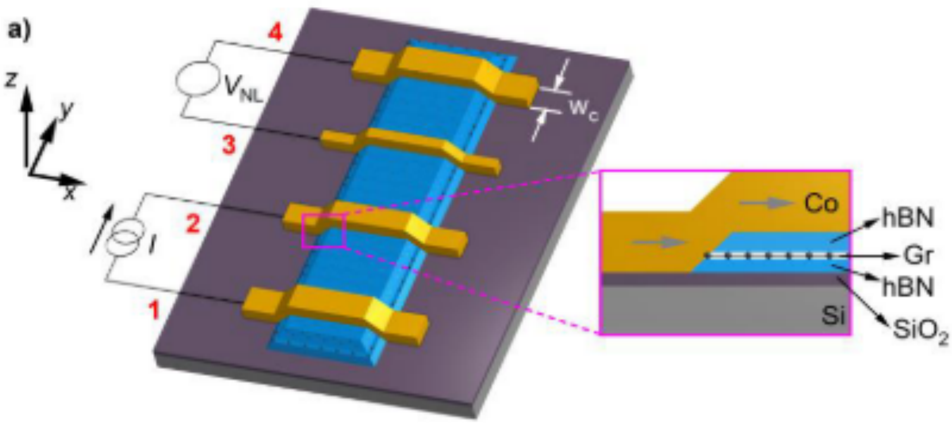

Fig. 1 Schematic illustration of a high-quality graphene spintronic device and 2D cross section (inset) of the device architecture using 1D contacts [3].

Acknowledgements: These works are the result of collaboration with Prof. Irina Grigorieva at the University of Manchester. Further work in Manchester in the area of high-frequency spintronics will be covered by Prof. Tom Thomson.

References:

[1] A. Avsar *et al.*, *Rev. Mod. Phys*. **92**, 021003 (2020).
[2] J. C. Toscano-Figueroa *et al.*, *Phys. Rev. Applied* **15**, 054018 (2021).
[3] V. H. Guarochico-Moreira *et al. Nano Lett.* (2022).
[4] L. Wang *et al.*, *Science* **342**, 614 (2013).
[5] J. Xu *et al.*, *Nat. Commun.* **9**, 2869 (2018).

Overview of spintronics in Manchester

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This presentation will provide an overview of recent and current research in magnetism and spintronics in Manchester. In addition to briefly mentioning work [1] that will be covered in other talks, the presentation will give our latest results on the lattice dynamics in FeRh thin films [2-3], the use of scanning probe microscopy to determine multiple physical parameters on the nanometer scale and progress towards the formation of an ordered magnetic phase in MnAl thin films [4].

Understanding the ultrashort time scale structural dynamics of the FeRh metamagnetic phase transition is a key element in developing a complete explanation of the mechanism driving the evolution from an antiferromagnetic to ferromagnetic state. Using the SACLA x-ray Free Electron Laser (x-FEL) we determine, with sub-ps time resolution, the time evolution of the (-101) lattice diffraction peak following excitation using a 35 fs laser pulse. The dynamics at higher laser fluence indicates the existence of a transient lattice state distinct from the high temperature ferromagnetic phase, Fig.1. By extracting the lattice temperature and comparing it with values obtained in a quasi-static diffraction measurement, we estimate the electron-phonon coupling in FeRh thin films as a function of laser excitation fluence. A model is presented which demonstrates that the transient state is paramagnetic and can be reached by a subset of the phonon bands. A complete description of the FeRh structural dynamics requires consideration of coupling strength variation across the phonon frequencies.

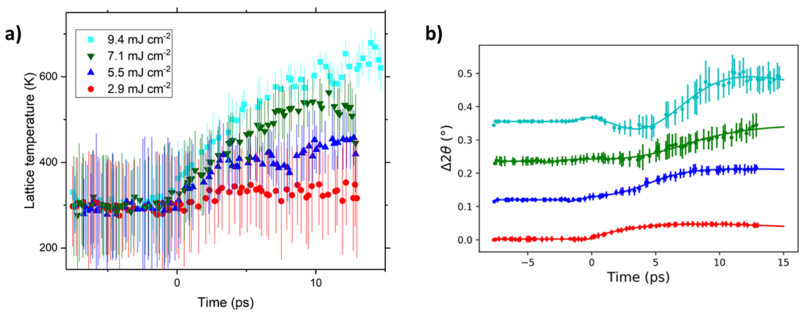

Figure 1 - Ultrafast behaviour of the FeRh (-101) Bragg peak and calculated lattice temperature following laser excitation.

One $L1_0$ binary alloy with potential for spintronic applications is MnAl. Neither Mn or Al show ferromagnetic ordering, however, when combined under the correct thermodynamic conditions (deposition and annealing temperatures) and an appropriate substrate template, the alloy provides magnetic properties similar to FePt.47, 48 Such properties are normally only found in materials containing 4f elements such as Pt or Pd. In the case of MnAl these desirable magnetic properties are only obtained over a small (~10 %) atomic composition window due to a complex phase diagram, hence a detailed understanding of composition is essential in developing these thin film materials.44 In recent years there have been relatively few reports on the fabrication of thin film MnAl due to the difficulties in creating the appropriate thermodynamic conditions and ensuring the correct stoichiometry. Here we show the capability of HAXPES to provide key compositional information in films that are only 50 nm thick [4].

Acknowledgements: These studies was partially supported by EPSRC grants EP/S033688/1, EP/K008412/1, EP/L01548X/1, EP/S019367/1 and EP/P025021/1.

References:
[1] https://nest.cs.manchester.ac.uk/publications-presentations/.
[2] M. Grimes *et al.*, *AIP Adv.* **12**, 035048 (2022).
[3] M. Grimes *et al.*, *Sci. Rep.* (In Press).
[4] B.F. Spencer *et al.*, *Faraday Discussions* (In press).

Synthetic antiferromagnetic skyrmions

Razan Aboljadayel,[1] Christopher Barker,[1] Kayla Fallon,[2] Simone Finizio,[3] Thomas Moore,[1] Gavin Burnell,[1] Damien McGrouther,[2] Stephen McVitie [2] and Christopher Marrows [1]

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Magnetic skyrmions are small topologically protected non-trivial spin textures with quasiparticle-like properties that have been observed in bulk non-centrosymmetric systems, thin films and nanolayers [1]. Skyrmions have attracted great attention as potential information carriers in spintronic devices such as racetrack memory devices [2]. However, the realisation of skyrmion-based applications is held back due to a few challenges such as their limited speed due to the skyrmion annihilation, stabilisation at room temperature and the ability to manipulate them at low power. However, it has been proposed that these issues can be overcome by using antiferromagnetically-coupled skyrmions [3].

Here, we report the skyrmions in synthetic antiferromagnetic (SAF) Ta/[Ru/Pt/CoB/Ru/Pt/CoFeB]$_5$/Ru/Pt structure which exhibit perpendicular magnetic anisotropy and Dzyaloshinkii-Moriya interaction. We will describe its current-driven dynamics observed by scanning transmission x-ray microscope, where the velocity was measured to be about 20 nm/s at a low current density of ~4×10^{11} A/m^2. We will also discuss our attempt to study the magnetisation dynamics in this structure near the ferromagnetic-antiferromagnetic transition using the time-resolved polar magneto-optical Kerr effect and highlight the challenges in designing skyrmion injection devices.

References:

[1] Y. Tokura and N. Kanazawa, *Chem. Rev.* **121**, 5, 2857 (2021).
[2] X. Zhang *et al.*, *Nat. Commun.* **7**, 10293 (2016).
[3] W L Gan *et al.*, *New J. Phys.* **20**, 013029 (2018).

Polarised neutron reflectometry characterisation of interfacial magnetism in an FePt/FeRh exchange spring

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Multilayer thin film systems with tuneable interlayer coupling have the potential to be functionalised for data storage [1], high-frequency broadband signal generation [2], and skyrmionic [3] devices. One such system is an exchange spring comprising two films with mutually orthogonal anisotropy axes, where the coercivity of the hard layer is reduced by its exchange coupling to the soft layer; this is the exchange spring mechanism. Here we present temperature- and applied field-dependent polarised neutron reflectometry (PNR) data on an exchange spring comprising an FePt layer with perpendicular magnetic anisotropy (PMA) and an in-plane FeRh layer. The antiferromagnetic to ferromagnetic phase transition in FeRh enables the exchange spring to be activated at ~80 °C, providing a promising route towards heat assisted magnetic recording (HAMR) with reduced operational temperatures.

By fitting simulated spin-resolved neutron reflectivity profiles to the measured PNR data, we determine the form of the magnetic scattering length densities (mSLDs), which are interpreted in terms of the competition between anisotropy, exchange coupling, and dipolar coupling as the magnetic phase transition progresses. The PNR data are combined with magnetometry and X-ray characterisation, allowing us to determine characteristic length scales over which the exchange spring mechanism is effective at ambient and elevated temperatures (Fig. 1).

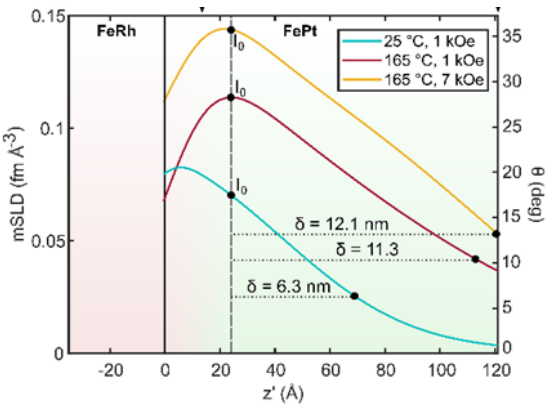

Fig. 1 The evolution of the mSLD through the depth of the FePt layer. The lengths δ characterise distance over which the mSLD decays, and hence the distance over which the FePt spins are reorientated. The right axis allows the data be interpreted in terms of the spin angle to the easy axis.

Acknowledgements: This study was partially supported by the Henry Royce Institute through EPSRC Grants No. EP/S019367/1 and No. EP/P025021/1. Experiments at the ISIS Neutron and Muon Source were supported by a beamtime allocation Grant No. RB1720270 (DOIs 10.5286/ISIS.E.RB1720270 and 10.5286/ISIS.E.RB1720270) from the Science and Technology Facilities Council.

References:

[1] J.–U. Thiele, S. Maat and E. E. Fullerton, *Appl. Phys. Lett.* **82**, 2859 (2003).
[2] T. Seifert *et al.*, *Nat. Photon.* **10**, 483 (2016).
[3] A. Fert *et al.*, *Nature Rev. Mater.* **2**, 17031 (2017).

Magnetic skyrmions for nanocomputing

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Nanoscale magnetic skyrmions are magnetic textures with a whirling vortex-like spin structure with distinct topological properties and intriguing dynamics [1,2]. Nanoscale chiral skyrmions have been identified as promising candidates for future energy-efficient devices with diverse functionality such as memory [2], Boolean computing [3], stochastic computing [4], reservoir computing [5,6], biomimetic/neuromorphic computing e.g. [7-11]. More recently they have also been proposed for use as information carriers in interconnects [12]. We show here our numerical results on multilayer skyrmionic nanosynapses tailored for room temperature (RT) operation with optimal synaptic resolution. When embedding such multilayer skyrmionic synapses in a deep spiking neural network (SNN), a high classification accuracy is achieved in the MNIST handwritten data set. The results suggest that the proposed skyrmionic nanosynapses are relevant for future energy-efficient neuromorphic edge computing [11]. While skyrmionic on-site memory, nanocomputing, and neuromorphic components have increasingly been investigated by the community, interconnects have been largely missing. We also propose an all-magnetic skyrmion-based topological multiplexing device that can serve as an interconnect, shown in Fig. 1 [12]. We evaluate the operational parameters (from ideal conditions (0 K) to room temperature) by simulating a tailor-designed magnetic multilayer heterostructure to demonstrate the potential of our proposed skyrmionic interconnect. Finally, we use strategically etched notches to introduce pipelining in order to achieve a superior throughput in multiplexing and demultiplexing signals.

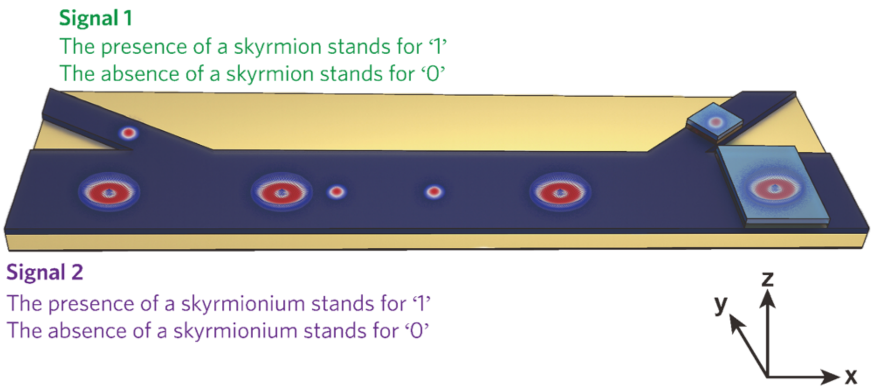

Fig. 1 Schematic of the proposed skyrmionic interconnect.

References:

[1] N. Nagaosa and Y. Tokura, *Nat. Nanotechnol.* **8**, 899 (2013).
[2] A. Fert, V. Cros and J. Sampaio, *Nature Nanotechnol.* **8**, 152 (2013).
[3] M. Chauwin *et al.*, *Phys. Rev. Appl.* **12**, 064053 (2019).
[4] D. Pinna *et al.*, *Phys. Rev. Appl.* **9**, 064018 (2018).
[5] D. Prychynenko *et al.*, *Phys. Rev. Appl.* **9**, 014034 (2018).
[6] D. Pinna, G. Bourianoff and K. Everschor-Sitte, *Phys. Rev. Appl.* 14, 054020 (2020).
[7] S. Li *et al.*, *Nanotechnology* **28**, 31LT01 (2017).
[8] Y. Huang *et al.*, *Nanotechnology* **28**, 1 (2017).
[9] T. Bhattacharya *et al.*, *IEEE Access* **7**, 5034 (2019).
[10] K. M. Soon *et al.*, *Nat. Electron.* **3**, 148 (2020).
[11] R. Chen *et al.*, *Phys. Rev. Appl.* **14**, 014096 (2020).
[12] R. Chen *et al., Phys. Rev. Res.* **2**, 043312 (2020).

Magnetoelasticity: Using strain to control magnetic switching in antiferromagnets

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Modern spintronics device conception relies on the cooperation in growth and characterisation of novel magnetic materials, and numerical simulation such as Density Functional Theory, Micromagnetics and Atomistic Spin Dynamics (ASD). This last one has proven to be useful in understanding the dynamics of processes essential to magnetic recording such as switching of magnetic domains. In this framework, different competing effective fields are taken into account in an energetic fashion where each term is constructed based on the symmetries of its physical origin. Alongside the famous Zeeman, Anisotropy and Dzyaloshinskii-Moriya interactions, there is also shape anisotropy which can be induced by deformation of the crystal lattice of magnetic materials. This inherently static term cannot describe dynamical deformation of a solid which one might encounter with phonon excitations due to mechanical stimulation or polarised laser pulses [1]. We have built a dynamical model based on a field theory approach combining ASD and tensor mechanics in a magneto-elastically coupled model based on the symmetries of magnetostriction. We have then used this model to investigate the influence on magnetoelastic coupling and external stress on the switching behaviour of an antiferromagnetic toy-model of NiO [2]. We have shown that it is in theory possible to improve the switching speed due to a Spin Transfer Torque of such an antiferromagnet by applying an external stress as can be seen in Figure 1.

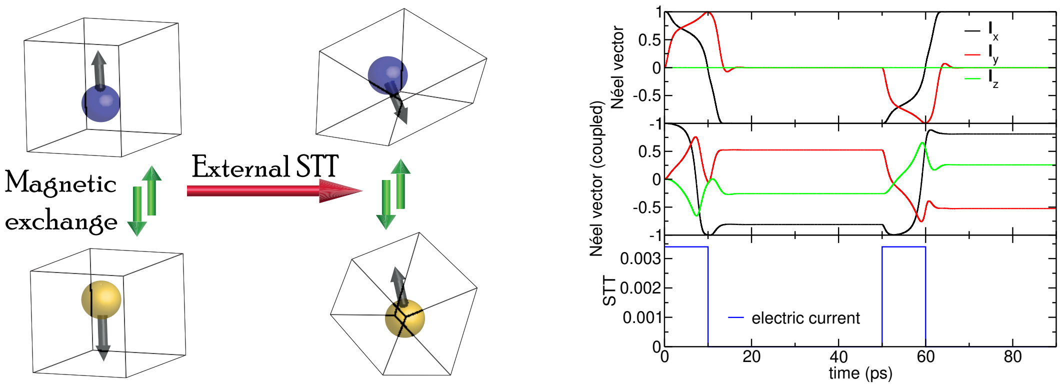

Fig. 1 Néel order parameter switching of antiferromagnet using spin transfer torque. Uncoupled vs magnetoelastic coupling with external stress.

Symmetry arguments which have led to the magnetoelastic form we have chosen (quadratic in magnetization) are, however, no longer essential for antiferromagnets where one may encounter so called piezomagnetism [3] (linear in magnetization). For materials where this interaction is encountered [4], it has two main advantages which are that it can be orders of magnitude stronger than regular magnetostriction and, being linear, it is also sign sensitive thus potentially much more useful for selective switching of domains using strain.

Acknowledgements: This study was supported by a joint CEA-Région Centre Val-de-Loire (doctoral fellowship grant number: 201600110872) and by EPSRC (grant number: EP/V037935/1).

References:

[1] A. M. Kalashnikova *et al.*, *Phys. Rev. B* **78**, 104301 (2008).
[2] T. Nussle *et al.*, *Phys. Rev. B* **100**, 214428 (2019).
[3] I. E. Dzyaloshinskii, *Sov. Phys. JETP* **6**, 621 (1958).
[4] A. S. Disa *et al.*, *Nat. Phys.* **16,** 937 (2020).

Guidelines for attaining optimal soft magnetic properties in FeAlSi films

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Sendust alloy ($Fe_{73.7}Al_{9.7}Si_{16.6}$) [1] is potentially suitable for application to tunnel magneto-resistive (TMR) sensors because of the high spin polarization of Δ_1 band and small magnetic anisotropy [2]. However, FeAlSi thin films have been poorly investigated for spintronic applications and the mechanism of soft magnetic properties was not clearly understood. The purpose of this study is systematic investigation of crystal and magnetic properties of FeAlSi films to realize their excellent soft magnetic properties. All films were deposited on MgO[001] substrates by DC/RF magnetron sputtering. The stacking structure is MgO-sub./MgO(20)/FeAlSi(30)/Ta(5) (thickness in nm). FeAlSi films with various compositions (shown in Table in Fig. 1) were deposited and annealed in-situ at T_{FeAlSi}=300–600℃ after the deposition. The crystal and magnetic properties were characterized by X-ray diffraction (XRD) and vibrating sample magnetometer (VSM).

Figure 1 shows T_{FeAlSi} dependence of magnetic anisotropy field H_k evaluated from magnetization curves. We confirmed the sign reversal of magnetocrystalline anisotropy (K_1) with increasing T_{FeAlSi} for FeAlSi films with Al-rich composition, and observed the minimum H_k of 0.43 Oe. The sign reversal of K_1 is presumably due to the volume balance of various ordered phases of D0$_3$-Fe_3Si, D0$_3$-Fe_3Al, B2-Fe_3Si, B2-Fe_3Al, and A2-FeAlSi. We simulated K_1 dependence on the Al concentration using bulk values of K_1 for each ordered phases [3,4] and ordering parameters experimentally measured by XRD. Fig. 2 shows the experimental and simulation results of K_1 for the compositions where K_1~0 was achieved. The simulated results were roughly in agreement with the experimental results, and the points of K_1~0 shifted to the Al-rich composition as atomic ordering decreased. We found that the FeAlSi films with excellent soft magnetic properties can be obtained by control of the film composition and annealing temperature to adjust the volume fraction of *D*0$_3$-Fe_3Al which only possesses the negative K_1 among the ordered phases in FeAlSi films. This is the first report in the world on FeAlSi film as a TMR sensor free layer material, which is expected to stimulate research in this field and accelerate practical applications for sensors.

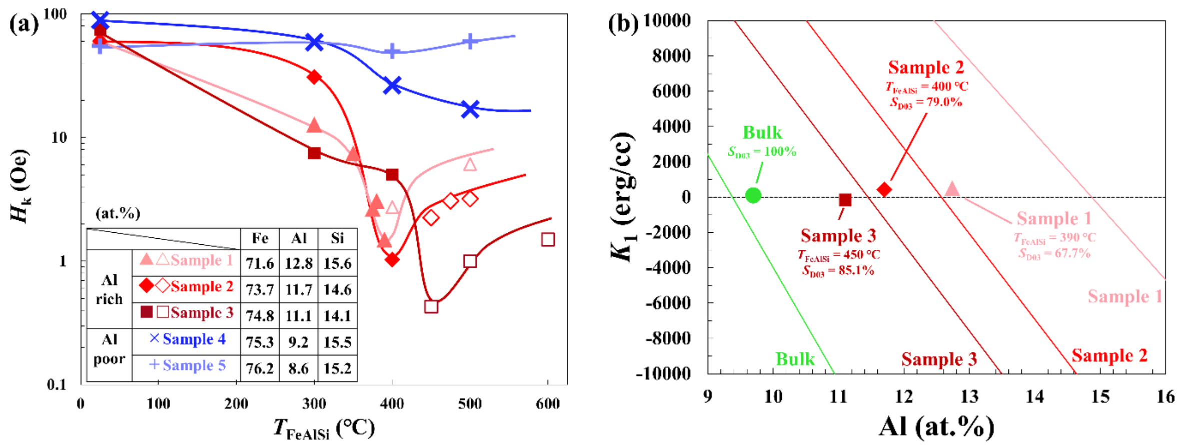

Fig. 1 (a) T_{FeAlSi} dependence of H_k for FeAlSi films with various compositions. (b) Experimental (plotted points) and simulation (solid lines) results of K_1 dependence on Al concentration.

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References:

[1] H. Masumoto and T. Yamamoto, *J. Jpn. Inst. Met.* **1**, 127 (1937).
[2] S. Akamatsu, M. Oogane *et al.*, *AIP Adv.* **11**, 045027 (2021).
[3] M. Takahashi *et al.*, *J. Jpn. Inst. Met.* **10**, 221 (1986).
[4] M. Goto and T. Kamimori, *Proc. Spring Secti. Meeting* **1982**, 198 (1982).

Structural investigation of CoIrMnAl Heusler alloy epitaxial films for spintronics applications

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A major area of research in the field of spintronics is the development of materials used for the fabrication of magnetic tunnel junctions (MTJ). Emergent computing technologies are already setting the demand for new MTJ electrode materials, namely, extremely high TMR ratios at room temperature [1]. Generally, the loss in TMR ratio with increasing temperature is thought to be due to loss of spin polarisation and desirable magnetic order at the interface of the electrode and the MgO tunnelling barrier [2]. Therefore, it is critical that any potential electrode material be a close crystallographic match to MgO and present consistent electronic character across a range of interfacial conditions.

A potential candidate for next-gen MTJ electrodes are quaternary Heusler alloys with equiatomic stoichiometry [3] i.e. having chemical formula XX'YZ. Recent theoretical studies have found that quaternary Heusler alloys of the form CoIrMnZ (Z= Al, Si, Ga, Ge) have near perfect spin polarisation due their half-metallic nature and have Curie temperatures above room temperature [4]. The fully ordered bcc-structure of these alloys is an excellent match to MgO. While swap-disorder within the unit can be used to tune the magnetic properties [5].

Here we have successfully deposited thin films of CoIrMnAl (~50nm) at room temperature with *B*2 chemical ordering using sputter deposition [6]. In-situ annealing at 500-600°C yields a lattice constant approximating the theoretical values. Magnetic measurements showed ferrimagnetic ordering and a Curie temperature of 400K; which is ~70% of the predicted value. Cross-section (S)TEM of the interfacial region reveals a route to improved performance via optimisation of the interfacial roughness.

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References:

[1] M. Zabihi *et al.*, *IEEE Trans. Comput.* **68**, 1159 (2019).
[2] Y. Miura, K. Abe and M. Shirai, *Phys. Rev. B* **83**, 214411 (2011).
[3] V. Alijani *et al.*, *Phys. Rev. B* **84**, 224416 (2011).
[4] T. Roy *et al.*, *J. Magn. Magn. Mater.* **498**, 166092 (2020).
[5] S. Yamada *et al.*, *Phys. Rev. B* **100**, 195137 (2019).
[6] R. Monma *et al.*, *J. Alloys Comp.* **868**, 159175 (2021).

Magnetic imaging of antiskyrmions in $Mn_{1.4}PtSn$ using Lorentz TEM and electron holography

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More than a decade has passed since the first experimental evidence of magnetic skyrmions in MnSi [1]. Since then, driven by their high potential for applications in future magnetic memory devices, skyrmions and related magnetic nano-objects of non-trivial topology have been in the focus of intensive research in the scientific community. Transmission electron microscopy (TEM) has proven a powerful tool to classify such magnetic textures as it provides for a detailed mapping of the magnetic structure in the specimen. Among the large variety of magnetic textures that have meanwhile been identified are Bloch-type skyrmions, Néel-type skyrmions and antiskyrmions.

The emphasis of this talk will be on the introduction of Lorentz TEM (L-TEM) and electron holography. Both techniques allow for the quantitative and high-resolution magnetic imaging of the volume of a sample by determining the 2D projected in-plane magnetic induction, thereby providing for a detailed mapping of the magnetic landscape within the material.

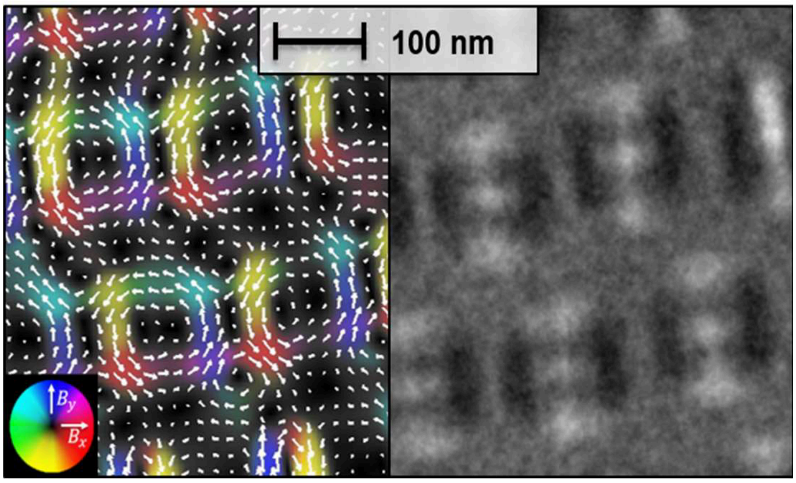

Fig. 1 Reconstructed direction map of the projected inplane magnetic induction of an antiskyrmion lattice in Mn1.4PtSn (Left). Defocused L-TEM image used for the reconstruction of this map (Right).

Both techniques differ in their experimental design and have their individual benefits and drawbacks, the understanding of which is essential in order to optimized the design and course of the experiment. The presentation will introduce the experimental basics and setups and demonstrate, how the magnetic textures are reconstructed from the raw experimental image data.

Examples for the application of these techniques will be given by the magnetic characterization of the inverse Heusler compound Mn1.4PtSn. The material is known to host a variety of different topologically protected magnetic textures such as, e.g., antiskyrmions (cf. Fig. 1) and will serve as a showcase to illustrate the application of the above techniques in current research [2,3].

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References:

[1] S. Mühlbauer *et al.*, *Science* **323**, 915 (2009).
[2] A.K. Nayak *et al.*, *Nature* **548**, 561 (2017).
[3] L. Peng *et al.*, *Nat. Nanotechnol.* **15**, 181 (2020).

Atomistic control of magnetic anisotropy

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Density Functional Theory is a powerful tool to calculate material properties purely from a knowledge of the structure of the system. In this talk, results from using DFT to simulate the magnetic anisotropy will be presented and some of the controlling factors will be discussed.

Towards molecular interface spintronics

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Material interfaces can play a significant role in the pursuit of long-term future information architectures which use sustainable nanomaterials operating at high frequencies. We combine spin filtering effects and photocurrents in metal-fullerene-metal oxide devices to generate a magnetic interface formed by spin polarised charge trapping. The mechanism is generated by photocurrents in the sample and is therefore determined by exciton formation. Transient absorption spectroscopy measurements show changes to the electronic states within ps of the optical pumping. We probe the interfacial magnetism by depth-sensitive magnetic characterization techniques such as X-ray magnetic circular dichroism of the Carbon K-edge in addition to low-energy muon spin rotation where the local magnetic field in buried interfaces can be accessed. Using time-resolved MOKE measurements, we show changes in the spin dynamics of the device during microwave irradiation, in effect demonstrating the ability to read the state of the device optically. The results open new paths of research to design hybrid magneto-optic structures operating at high frequencies for sensing, computing, and information storage.

Acknowledgements: This work was supported by EPSRC grants no. EP/M000923/1, EP/K036408/1, EP/S031081/1 and EP/S030263/1. MV acknowledges Mineco grant FIS2016-78591- C3-2-R (AEI/FEDER, UE). ALBA beamtime access via proposal IDs 2017092385 and 2015091530. We acknowledge use of the N8 High Performance Computing (HPC) (EPSRC EP/K000225/1), ARCHER (via the UK Car–Parrinello Consortium, EP/K013610/1 and EP/P022189/2), and UK Materials and Molecular Modelling Hub (EPSRC EP/P020194/1) HCP facilities.

Twist-angle control of collinear Edelstein effect in van der Waals heterostructures

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Spin-charge conversion processes in graphene-based van der Waals (vdW) heterostrucutres have been the subject of many theoretical and experimental studies over the past decade [1, 2]. The field of spintronics prides itself on uncovering the novelty of these processes with the perspectives of technology and fundamental physics in mind [3]. In recent years, the study of twisted vdW heterostructures [4], with precise relative rotation angle between the layers, has given birth to a new field known as *twistronics*.

In this talk, we look at the unification of spintronics with twistronics by studying the proximity-induced spin-orbit coupling (SOC) in graphene-transition metal dichalcogenide (G-TMD) bilayers. Previous works [5] have found that the introduction of a twist between the graphene and TMD layers allows for the tuning of the SOC strength. Twisting enables non-trivial spin-textures to manifest on the Rashba-split graphene bands, such that spin and momentum are no longer locked at right-angles to one another. Using linear response theory, we show that such spin and momentum eigenstates generate a non-zero spin-current response parallel to the applied electrical current at non-zero twist angles. Accounting for short-range impurities and twist-disorder, we predict the existence of a robust *collinear Edelstein effect* without the need for magnetic materials or skew scattering.

**These authors contributed equally to the results of this research.*

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References:

[1] M. Offidani, M. Milletarì, R. Raimondi and A. Ferreira, *Phys. Rev. Lett.* **119**, 196801 (2017).
[2] A. Avsar, H. Ochoa, F. Guinea, B. Özyilmaz, B. J. van Wees and I.J. Vera-Marun, *Rev. Mod. Phys.* **92**, 021003 (2020).
[3] W. Han, R. K. Kawakami, M. Gmitra and J. Fabian, *Nat. Nanotechnol.* **9**, 794 (2014).
[4] R. Ribeiro-Palau, C. Zhang, K. Watanabe, T. Taniguchi, J. Hone and C. R. Dean, *Science* **361**, 690 (2018).
[5] Y. Li and M. Koshino, *Phys. Rev. B* **99**, 075438 (2019); A. David, P. Rakyta, A. Kormányos and G. Burkard, *Phys. Rev. B* **100**, 085412 (2019); C. G. Péterfalvi, A. David, P. Rakyta, G. Burkard and A. Kormányos, *arXiv:2111.02781v2* [cond-mat.mes-hall].

Gas phase synthesis of magnetic core-shell nanoparticles

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Magnetic nanoparticles continue to attract a great deal of attention related to their potential use in biomedical, environmental, and data storage applications [1,2]. The ability to produce pure magnetic particles is of great interest and as such the use of high vacuum gas phase systems has become increasingly popular. The sputtering of a metal target with a plasma and the subsequent aggregation of the metal vapour allows for pure, crystalline particles to be produced with relative ease. The size distribution of the forming particles can also be controlled through changing the various parameters of the source during growth. Due to differential pumping, the particles then form a beam which can then be modified or manipulated *in-situ*.

One such modification is through the use of core-shell coating where the original particles can be coated in a secondary material. By coating a ferromagnetic core with an anti-ferromagnetic shell, exchange bias can occur and through careful selection of coating material and the size of the original particle the critical temperature for superparamagnetic behavior can be increased [3]. Coupling the magnetic core with a noble metal can also lead to functionalized particles with magnetic and plasmonic responses [4]**.** However, this can lead to the nano-Kirkendall effect occurring and thus hollow particles forming [5].

In this talk, the development and operation of a gas aggregation cluster source will be discussed, shown schematically in Fig. 1, with results presented on the production of Fe/Fe oxide nanoparticles as well as coating the particles with Ag. The long-term stability of the particles will also be shown, with environmental transmission electron microscopy (eTEM) studies showing the in-depth oxidation process of the Fe/Fe oxide nanoparticles as well as giving insights into the hollowing process these particles may undergo.

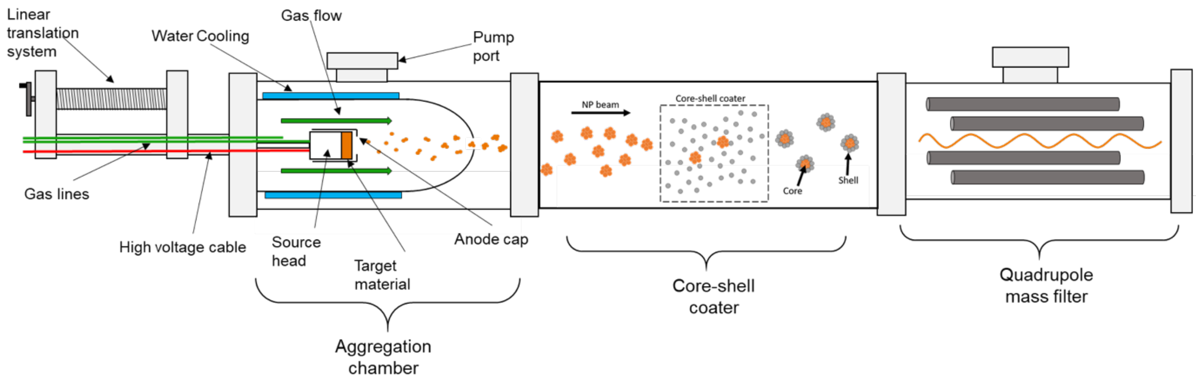

Fig. 1 Schematic of a gas aggregation cluster source and core-shell coater that enables the production of size-selected complex magnetic nanoparticles.

References:

[1] M. Walker *et al.*, *ACS Appl. Nano. Mater.* **3**, 6 (2020).
[2] A. Pratt *et al.*, *Nat. Mater.* 13, 26 (2014).
[3] V. Skumryev *et al.*, *Nature* **423**, 6942 (2003).
[4] J. Ramade *et al., J. Phys. Chem. C.* ***123****, 25 (2019).*
[5] Y. Yin *et al.*, *Science* **304**, 5671 (2004).

Spectroscopy study of ferromagnetic topological insulator

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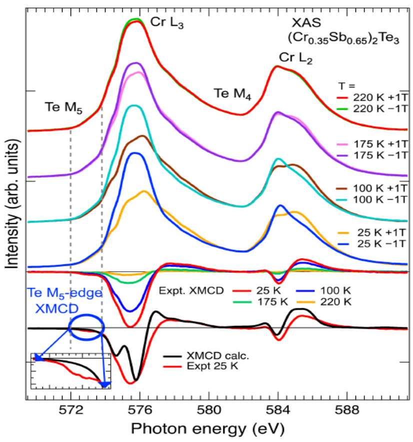
We study the electronic and magnetic properties of ferromagnetic topological insulator $(Cr_{0.35}Sb_{0.65})_2Te_3$ with a high ferromagnetic Curie temperature (T_C~ 185 K) by using Cr L-edge and Te M-edge x-ray absorption spectroscopy (XAS), x-ray magnetic circular dichroism (XMCD) and angle-resolved photoemission spectroscopy (ARPES). The temperature*(T)*-dependent (25 K-220 K) XMCD results showed a systematic and spin-selective leading edge shift of Cr 3*d* and Te 5*p* unoccupied density of states across T_c, resulting in a magnetic gap opening. The *T*-dependent XMCD signal intensity and the magnetic gap energies are consistent with bulk magnetization. The full multiplet charge transfer model calculation with a negative charge transfer energy showed a good agreement with the experiment. The ARPES measurement showed Dirac-cone surface states (SS) above and below T_c, implying that the band inversion between the Sb and Te orbital is maintained even at high Cr doping level, consistent with a negative charge transfer energy. These results establish a direct link between Cr 3*d* dopant states and the Te 5*p* SS forming the magnetic gap.



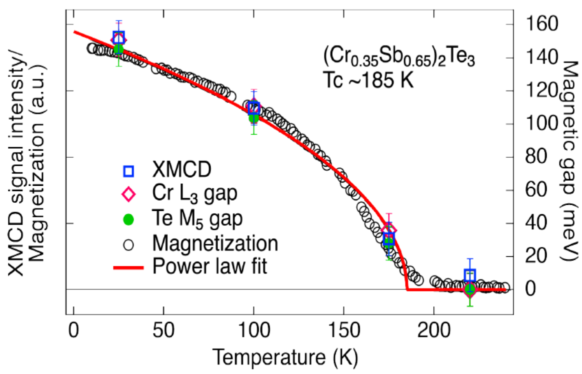


Fig. 1. Top panel: *T*-dependent Cr L-edge and Te M-edge XAS spectra of $(Cr_{0.35}Sb_{0.65})_2Te_3$ with an applied magnetic field of ± 1 Tesla. Bottom panel: T-dependent Cr L-edge and Te M-edge XMCD spectra, as well as the Cr 3d XMCD calculation compared with the *T* = 25 K XMCD spectrum. The Te M5 XMCD signal is marked and expanded in the inset. Fig. 2. The XMCD signal and magnetization together with the magnetic gaps as a function of T.

Towards functional topological insulator films

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Topological insulators have emerged as a promising basis for creating a state of matter, where the protected states can be produced at the surface of the material via the spin-momentum locking by the constraints of time-reversal symmetry[1,2]. In this study, we are looking for the functional topological insulator via the local ion implantation method. We are able to fabricate various topological insulators such Bi_2Se_3, Bi_2Te_3 $(Bi_xSb_{(1-x)})_2Te_3$, Sb_2Te_3. Via the local ion implantation method, for instance, we could obtain a regional magnetic topological insulator by doping with Mn or superconducting by doping with Ir. The findings of this study could open a route for the spintronics and superconductivity applications.

We use molecular beam epitaxy and lithography methods for fabricating the devices. We do transport and AFM/MFM characterization in a cryostat.

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References:

[1] S. Rachel, *Rep. Prog. Phys.* **81**,116501 (2018).
[2] Y. Tokura, K. Yasuda and A. Tsukazaki, *Nat. Rev. Phys.* **1**,126 (2019).

The field-emission regime of scanning tunneling microscopy for spintronic materials

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The field-emission regime of a Scanning Tunneling Microscope (STM) occurs when the tip is retracted from the sample by 5 to 100 nm, and by applying a suitable junction bias voltage (-10 to -100 V tip bias in respect to the sample). In this regime the direct electron tunneling between the ultimate atoms on the tip apex and the sample surface underneath is forbidden, but a sharp tip becomes a source of electrons due to field emission [1]. In this regime the electrons arriving from the tip to the sample cause the generation of secondary electrons (elastic and inelastically scattered) on the sample surface, which can escape from the tip-sample junction. Such electrons may be collected by several means and analysed.

The strong dependence of the physical properties of the secondary electrons on the nature of the sample surface, due to their low energy (<100 eV), makes complementary information accessible. Besides the absorbed current maps and the z-piezo displacement images of the surface (as in STM), chemical and magnetic contrast with nanometre scale resolution can be achieved on the same region [2, 3]. For example, the detection of spin polarised secondary electrons generated in magnetic thin films such as Co/Pt(111) or Fe/W(110), has been used for magnetic imaging of the different magnetic domains [4].

In this talk we want to present the potential application of this spectroscopy/microscopy technique to investigate magnetic and electronic properties of magnetic nanostructures and 2D spintronic materials.

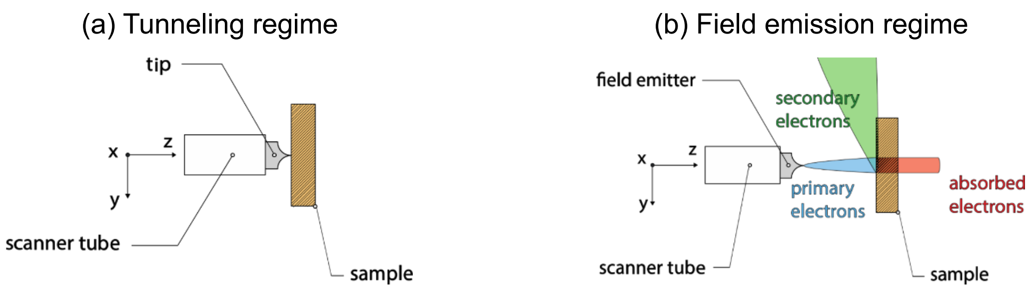

Fig. 1 (a) Scheme of the tunneling regime of STM: Tip and sample are in tunneling contact. b) Scheme of field emission regime of STM: Tip acts as source of primary electron beam (in blue), partially absorbed by the sample (in red) and generating elastically or inelastically scattered electrons (in green) which can escape the junction and eventually be collected by a detector.

Acknowledgements: This project is supported by EPSRC grant EP/V012126/1 (SEE MORE MAKE MORE: Secondary Electron Energy Measurement Optimisation for Reliable Manufacturing of Key Materials).

References:

[1] R. Young, J. Ward and F. Scire, *Rev. Sci. Inst.* **43**, 999 (1972).
[2] D. A. Zanin *et al.*, *Proc. R. Soc.* A **472** :20160475 (2016).
[3] L. De Pietro *et al.*, *Sci. Rep.* **7**, 13237 (2017).
[4] U. Ramsperger *et al.*, *Appl. Phys. Lett.* **115**, 112402 (2019).

Spin-orbit induced phenomena at ferromagnet/oxide and ferromagnet/2D material interfaces from first principles

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Spin-orbit coupling (SOC) at material interfaces leads to the emergence of a wealth of phenomena such as perpendicular magnetic anisotropy (PMA) and Dzyaloshinskii–Moriya interaction (DMI). Magnetic tunnel junctions based on Co(Fe)/oxide and Co/graphene interfaces have attracted much attention due to their low spin-orbit coupling but yet interesting magnetic and spin-orbitronic properties [1,2]. Using first-principles calculations, we investigate both PMA and DMI emerging at such interfaces.

In the first part of the talk, the correlation between temperature dependence of magnetic anisotropy and magnetization in typical Fe/MgO structures is addressed [3]. In an ideal interface, the temperature-dependence of the total and layer-resolved anisotropy follow the Callen and Callen scaling power law and thus intrinsic properties cannot explain deviations from this law. In this respect, we show that such deviations observed experimentally can be attributed to two macroscopic mechanisms: the presence of a magnetic dead layer or the spatial fluctuations of the interfacial PMA. We anticipate that those results will help in understanding the thermal stability of the storage layer magnetization in STT-MRAM applications.

In the second part, we demonstrate a significant PMA and a large DMI at Co/2D materials (graphene or h-BN) interfaces [4]. The PMA at the Co/h-BN interface is preserved as in the case of graphene coverage, thanks to the hybridization of d_{z^2} orbitals of Co with p_z ones of 2D materials. By comparing the two interfaces, it is found that the DMI in Co/h-BN increases as a function of Co thickness and beyond three monolayers stabilizes with one order of magnitude larger values compared to those at Co/graphene, where the DMI shows opposite decreasing behavior. The Rashba constant in the case of Co/h-BN is found to be at least twice larger than that of graphene/Co, giving rise to the larger DMI values. The difference between the two interfaces is explained by the presence of two competing dipoles at the graphene/Co interface compared to only one dipole at the Co/h-BN interface. These findings open up further possibilities towards integrating 2D materials in spin−orbitronic devices.

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References:
[1] B. Dieny & M. Chshiev, *Rev. Mod. Phys.* **89**, 025008 (2017).
[2] H. X. Yang *et al*., *Nano Lett.* **16**, 145 (2016).
[3] F. Ibrahim et al., *arXiv:2011.02220* (2022).
[4] A. Hallal et al., *Nano Lett.* **21**, 7138 (2021).

Exchange constant determination using multiple-mode FMR perpendicular standing spin waves

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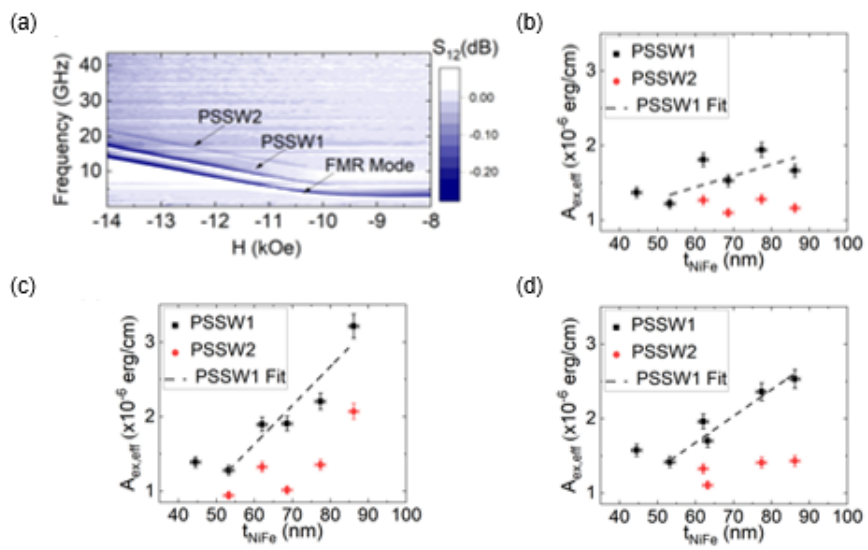

Fig. 1 a) Out-of-plane spin-wave spectra of a Ta capped NiFe thin film with t(NiFe)=77 nm as a function of applied field and frequency. (b-d) The variation in apparent exchange constant (Aex, app) determined using the Kittel model for each capping layer case.

The exchange constant (A_{ex}) is recognised as one of the fundamental properties of magnetic materials [1]. However, its accurate experimental determination remains a particular challenge. In thin films, recent literature uses dynamic measurements exploiting Perpendicular Standing Spin Waves (PSSWs) to extract A_{ex}, typically through a measurement of the first order PSSW mode and a subsequent analysis assuming rigid surface pinning is present (Kittel model) [2-4]. Here, we present a systematic study of multiple PSSW modes in NiFe films using Vector Network Analyser-Ferromagnetic Resonance Spectroscopy (VNA-FMR) as a function of thickness (t_{NiFe}) and capping layer material (uncapped, Ta, Pt) [5]. An example of measured PSSW resonances is shown in Fig. 1a. It is shown that an analysis of PSSW resonant modes using the Kittel model provides an A_{ex} that varies with mode number, t_{NiFe} and capping layer material (Fig. 1(b-d)). This is clearly inconsistent with the physical expectation that the A_{ex} of a material is single valued for a given set of thermodynamic conditions (temperature etc.). To resolve this inconsistency, we use a more general exchange boundary condition [2] (of which the Kittel model is a particular case) and show through a comprehensive set of micromagnetic simulations that a dynamic pinning mechanism originally proposed by Wigen [6] is able to reproduce the experimental results using a single value of A_{ex}. Our findings support the utility of short wavelength PSSWs to determine the A_{ex} in magnetic thin films, though indicate that the A_{ex} obtained has a weak dependency on the material immediately adjacent to the magnetic layer.

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References:

[1] J. M. D. Coey, *Magnetism and Magnetic Materials* (2010).
[2] G. T. Rado *et al.*, *J. Phys. Chem. Solids* **11**, 315 (1959).
[3] I. S. Maksymov *et al.*, *Phys. E: Low-Dimensional Syst. Nanostr.* **69**, 253 (2015).
[4] C. Kittel, *Phys. Rev.* **110**, 1295 (1958).
[5] H. J. Waring *et al.*, (Submitted).
[6] P. E. Wigen *et al.*, *Phys. Rev. Lett.* **9**, 206 (1962).

3D spintronics

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Dynamics of antiferromagnetically coupled skyrmions in synthetic antiferromagnet

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Magnetic skyrmions, topologically stabilized quasi-particles, have attracted attention not only from fundamental physics but also from device applications[1]. The magnetic skyrmions can be easily stabilized at room temperature by an interfacial Dzyaloshinskii-Moriya interaction (DMI) and can be efficiently controlled electrically through spin-orbit torques (SOT)[2]. In particular, ferrimagnetic/antiferromagnetic skyrmions which consist of antiferromagnetically (AF) coupled two skyrmions at each sublattice are promising candidates for such skyrmionic device applications due to the inhibition of the skyrmion Hall effect (SkHE)[3,4] which is a diagonal motion along with current flow direction, the absence of the Walker breakdown stemming from twisted domain wall[5], and its scalability[6].

Here we study the dynamics of AF-coupled skyrmions in a synthetic antiferromagnetic (SyAFM) system consisting of AF-coupled two ferromagnetic layers through interlayer exchange coupling via non-magnetic interlayer. The SyAFM system allows us to control pinning effect which is a crucial factor in investigating the intrinsic skyrmion dynamics, which is a significant advantage as compared to conventional amorphous ferrimagnetic/intrinsic (crystalline) antiferromagnets.

Our work comprises two parts to comprehensively cover the full dynamics range. The first one is about the current-induced deterministic motion[7], where we show the current-induced motion of skyrmions with suppressed SkHE even at room temperature in the SyAFM system. In the second part, we demonstrate the first observation of thermal diffusive dynamics for SyAFM skyrmions, enabling us to uncover the effect of topology on the diffusive motion of magnetic skyrmions. Our findings which shed light on the topological effect on the skyrmion dynamics indicate that AF-coupled magnetic skyrmions are promising for not only deterministic devices e.g. skyrmion racetrack memory[8] but also unconventional computing devices[9,10] that are actively making use of stochasticity.

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References:

[1] N. Nagaosa and Y. Tokura, *Nat. Nanotechnol.* **8**, 899 (2013). [2] S. Woo *et al.*, *Nat. Mater.* **15**, 501 (2016). [3] X. Zhang *et al.*, *Nat. Commun.* **7**, 10293 (2016). [4] J. Barker and O. A. Tretiakov, *Phys. Rev. Lett.* **116**, 147203 (2016). [5] I. Lemesh and G.S.D. Beach, *Phys. Rev. B* **98**, 104402 (2018). [6] F. Büttner *et al.*, *Sci. Rep.* **8**, 4464 (2018). [7] T. Dohi *et al.*, *Nat. Commun.* **10**, 5153 (2019). [8] A. Fert *et al.*, *Nat. Nanotechnol.* **8**, 152 (2013). [9] J. Zázvorka *et al.*, *Nat. Nanotechnol.* **14**, 658 (2019). [10] Y. Jibiki *et al.*, *Appl. Phys. Lett.* **117**, 082402 (2020).

Atomistic simulations on imprinting of skyrmion textures from a ferromagnet to an antiferromagnet

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Antiferromagnetic skyrmions encompass various advantageous properties over their ferromagnetic counterparts, including a vanishing net magnetization and a vanishing net topological charge. The former provides robustness against perturbations by external magnetic fields and while the latter prohibits the skyrmions from acquiring a transversal velocity. Due to the zero net magnetization, however, nucleation of the antiferromagnetic skyrmions tends to be challenging and therefore imprinting from a ferromagnet via exchange bias coupling could be an attractive solution for this issue.

The exchange bias effect in γ-IrMn/ferromagnet bilayers originates from the coupling of ferromagnetic spins to the uncompensated interfacial IrMn spins that arise from structural disorder [1]. This coupling allows for the ferromagnet to modify the spin structure at the interface of the antiferromagnet and thereby serves as a premise for the imprinting of magnetic textures from the ferromagnet to the antiferromagnet. Such imprinting has been previously demonstrated with magnetic vortices [2], and more recently, with skyrmion textures in Py/Co/Pt/IrMn structures [3].

Here we use the atomistic simulation software VAMPIRE [4] to investigate the skyrmion imprinting from Py/Co ferromagnetic bilayer into a γ-IrMn layer. In this talk I will discuss the establishing of a simulation system corresponding to the experimental system used in reference [4], as well as the initial demonstration of skyrmion nucleation in the ferromagnetic layer. I will also detail the next steps in this investigation of the nucleation, stability and dynamics of antiferromagnetic skyrmions.

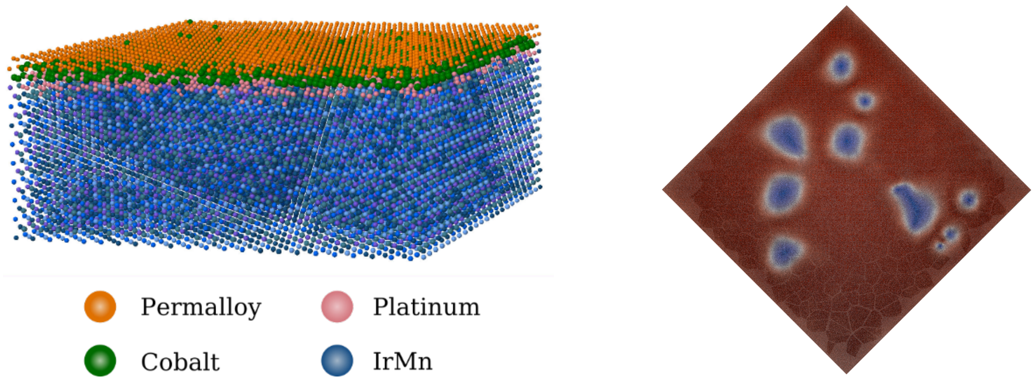

Fig. 1 (Left) Simulation system consisting of a Py/Co/Pt/IrMn structure, and (Right) Skyrmions in the Py/Co ferromagnetic layer of the simulation system.

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References:

[1] S. Jenkins *et al.*, *Phys. Rev. B* **102**, 140404(R) (2020).
[2] G. Salazar-Alvarez *et al.*, *Appl. Phys. Lett.* **95**, 012510 (2009).
[3] K. G. Rana *et al.*, *Appl. Phys. Lett.* **119**, 192407 (2021).
[4] R. F. L. Evans *et al.*, *J. Phys.: Condens. Matter* **26**, 103202 (2014).

Optical thermometry for investigating spin caloritronics

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Spin caloritronics is the research field of studying the interconversion between spin, charge, and heat currents [1,2]. Some of the spin-caloritronic phenomena that output heat currents have gained much attention for applying thermal management technologies. The spin Peltier effect (SPE) [3,4] and the anomalous Ettingshausen effect (AEE) [5] are the representative example of such phenomena; the former generates a heat current from a spin current at the junction comprised of a magnetic material, whereas the latter is one of the magneto-thermoelectric effects in a ferromagnetic metal. These phenomena have been investigated by employing the thermal measurement techniques with high sensitivity. Although early study of the SPE was conducted by the contact-type thermometry, such measurements are often disturbed by the heat loss to the temperature detectors. To solve this problem, the non-contact type temperature measurements, such as the lock-in thermography [4] and the optical thermometry called lock-in thermoreflectance (LITR) [6] has been introduced the spin caloritronics. In this presentation, I will talk about the usability of LITR method for investigating the spin-caloritronic phenomena that output heat currents.

The LITR is a combination of a lock-in detection and an optical thermometry using the temperature dependence of reflectivity. The sample used in this study consists of a metal film on a substrate, where the spin-caloritronic phenomena including the SPE and AEE appear. When an ac charge current and an external magnetic field are applied to the sample, the temperature modulation induced by the SPE and/or AEE occurs. This temperature modulation is detected by monitoring the intensity change of the reflected light from the sample surface covered with the Au transducer. Since the Joule heating contribution has the higher-harmonic component, it can be separated from the spin-caloritronic phenomena by using the lock-in detection.

Since the LITR captures the MHz-level thermal response, it can reveal the different frequency response of the SPE and AEE. The lock-in frequency dependence of the SPE-induced temperature amplitude in $Y_3Fe_5O_{12}$/Pt junction gradually decreases, whereas that of the AEE-induced temperature amplitude in Ni film shows almost constant. The difference is attributed to the different length scale of the heat current; while the transient response of the AEE is determined by the thickness of Ni layer, that of the SPE is determined by the length scale of the SPE-induced heat current in the $Y_3Fe_5O_{12}$ layer [6].

I will also report our on-going result of the LITR measurement for the Pt/antiferromagnetic insulator NiO/ferromagnetic metal junction system. We measured the NiO thickness dependence of the temperature amplitude due to the spin-caloritronic phenomena in the trilayer system. Our optical LITR method can successfully estimate the spin transmission length of NiO, which is consistent with the previous reports using the electrical measurement [7,8].

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References:

[1] G. E. W. Bauer *et al.*, *Nat. Mater.* **11**, 391 (2012).
[2] K. Uchida, *Proc. Jpn. Acad., Ser. B* **97**, 69 (2021).
[3] J. Flipse *et al.*, *Phys. Rev. Lett.* **113**, 027601 (2014).
[4] S. Daimon *et al.*, *Nat. Commun.* **7**, 13754 (2016).
[5] T. Seki *et al.*, *Appl. Phys. Lett.* **112**, 152403 (2018).
[6] T. Yamazaki *et al.*, *Phys. Rev. B* **101**, 020415(R) (2020).
[7] Y. Wang *et al.*, *Science* **366**, 1125 (2019).
[8] T. Ikebuchi *et al.*, *Appl. Phys. Express* **14**, 123001(2021).

Magnetization dynamics in thin film $Mn_2Au/Ni_{80}Fe_{20}$ bilayers

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The significant difference in the magnetization dynamics of ferromagnetic (FM) and antiferromagnet (AFM) materials could potentially be exploited in applications integrating AFM materials in high-frequency spintronic devices. A promising approach to enhance the FM spin dynamics frequencies and control FM spin wave dispersions might be the combination of FM and AFM thin-film layers with interfacial exchange coupling.

We study the magnetization dynamics of the $Mn_2Au/Ni_{80}Fe_{20}$ thin film bilayer system. This system allows us to control the Mn_2Au Néel vector orientation with moderate in-plane external magnetic fields depending on $Ni_{80}Fe_{20}$ layer thickness [1]. Mn_2Au furthermore shows strong spin-orbit torque efficiency [2] making this system intriguing for all-electrical control of magnetization direction. The $Ni_{80}Fe_{20}$ thickness is varied to study the effect of the $Mn_2Au/Ni_{80}Fe_{20}$ interface on $Ni_{80}Fe_{20}$ spin dynamics. Broadband Ferromagnetic resonance and Brillion light scattering experiments reveal that interfacial exchange coupling causes an increase in the resonance frequency of $Ni_{80}Fe_{20}$. This increase is inversely proportional to the thickness of the $Ni80Fe_{20}$ layer as shown in Figure 1.

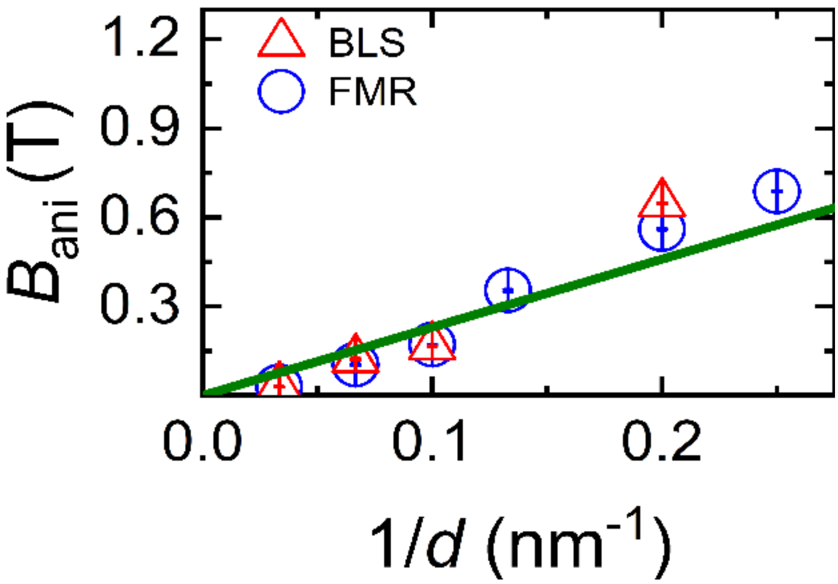

Fig 1: The dependence of the anisotropy field on the NiFe thickness *d* obtained from FMR and BLS measurements.

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References:

[1] Bommanaboyena *et al.*, *Nat. Commun.* **12**, 6539 (2021).
[2] Bodnar *et al.*, *Nat. Commun.* **9**, 348 (2018).

Spin-orbit torques in ferromagnetic heterostructures

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Thin film magnetic heterostructures can host complex magnetic textures, hybrid spin dynamics, and interfacial spin torques [1]. They therefore provide a promising platform for magnon spintronics. Over the last decade, spin-orbit torques (SOTs) have attracted significant research activity since they are promising for ultrafast and energy efficient spintronic devices.

SOTs can be used to electrically control the spin dynamics, while inverse SOTs enable electrical detection of spin dynamics. This approach has been established as an important building block for applied spintronic phenomena ranging from magnetic memory devices to novel spin-based computational approaches. Typically, SOTs are generated in bilayers of ferromagnets and heavy metals such as Pt. Here, based on theoretical predictions [2], we study the spin-to-charge conversion in ferromagnetic materials with high spin-orbit interaction. In particular, we chose perpendicular magnetic anisotropy (PMA) multilayers Co-Ni and Co-Pt. We investigate the spin dynamics and SOTs [3] of corresponding purely metallic ferromagnetic thin film in-plane anisotropy (IPA) / PMA hybrid systems using vector network analyzer ferromagnetic resonance spectroscopy (VNA-FMR). In our experiments, we excite spin dynamics in the IPA CoFeB layer and inductively detect the generated electrical currents in the PMA layers.

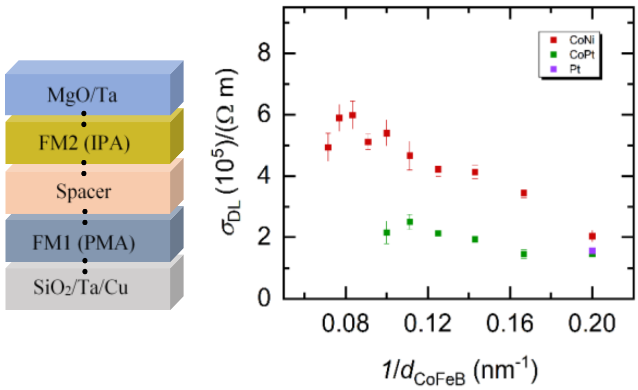

Fig. 1 (a) Schematic view of hybrid thin film stack. (b) Measured thickness dependent damping-like spin-orbit torque conductivity [2] for SiO2/Ta/Cu/[Co-Ni]/Cu/CoFeB/MgO/Ta and SiO2/Ta/Cu/[Co-Pt]/Cu/CoFeB/MgO/Ta.

As demonstrated in Figure 1, we observe substantial damping-like SOTs in both PMA layers. The SOTs in CoNi/Cu/CoFeB are comparable to those observed in Pt/CoFeB [4] and Pt/NiFe [5] heterostructures using the same technique and similar layer thicknesses. We discuss the evolution of the SOTs with CoFeB thickness and PMA layer composition.

Acknowledgements: We acknowledge financial support by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) via TRR 173 “Spin+X” 268565370 (projects B02 and B13).

References:

[1] S. Klingler *et al.*, *Phys. Rev. Lett.* **120**, 127201 (2018).
[2] A. Davidson *et al.*, *Phys. Lett. A* **384**, 126228 (2020).
[3] A. J. Berger *et al.*, *Phys. Rev. B* **97**, 94407 (2016).
[4] M. Meinert *et al.*, *Phys. Rev. Appl.* **14**, 064011 (2020).
[5] A. J. Berger *et al.*, *Phys. Rev. B* **98**, 024402 (2018).

Thin films from the Royce deposition system

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The Royce Deposition System is a multi-technique, multi-chamber facility for growth of thin films. Four deposition chambers with molecular beam epitaxy (MBE), sputtering and pulsed laser deposition (PLD) capabilities are linked by UHV transfer chambers (see figure 1). This allows for the creation of interfaces between a wide range of different thin-film materials, including Bi_2Se_3/C_{60}, Nb/PtCo and $BiFeO_3$/CoFeB. Methodology of your study to be added.

I will describe the capabilities of the equipment and show some of the materials that we've produced. I'll provide a brief tour of results from materials grown in the chamber, including superconducting memory devices [1] for cryogenic computing.

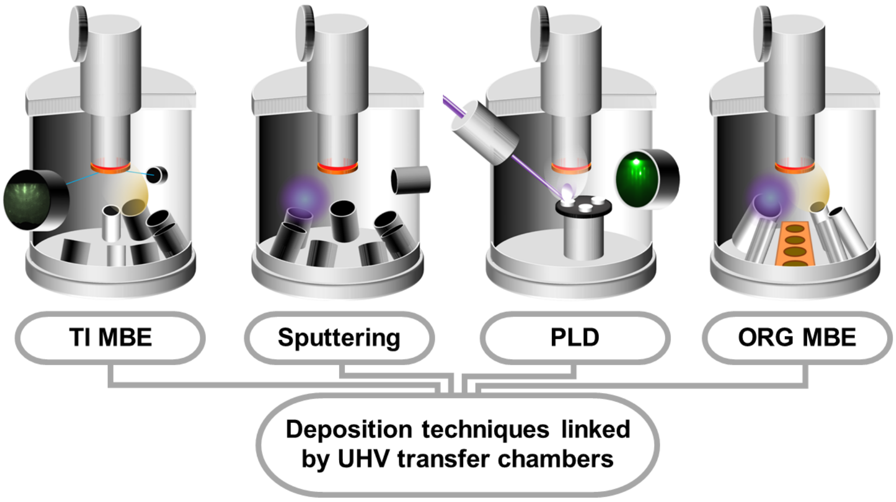

Fig. 1 Schematic of the Royce Deposition System.

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Reference:

[1] N. Satchell *et al.*, *Appl. Phys. Lett.* **116**, 022601 (2020).

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