Abstracts Book

International Workshop on Topological Structures in Ferroic Materials

8–10 August 2017
University of Leeds, Leeds, UK

Organised by the IOP Magnetism Group

IOP Institute of Physics

International Workshop on Topological Structures in Ferroic Materials

Tuesday 8 August 2017

Emergent chirality in oxide superlattices (Keynote)

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University of California, USA

The complex interplay of spin, charge, orbital, and lattice degrees of freedom has provided for a plethora of exotic phase and physical phenomena. Among these, in recent years, topological states of matter and spin textures have emerged as fascinating consequences of the electronic band structure and the interplay between spin and spin-orbit coupling in materials. In this lecture, I will discuss work on oxide superlattices that leverage the competition between charge, orbital, and lattice degrees of freedom. I will paticularly focus on superlattices of $PbTiO_3/SrTiO_3$ as a model system in which we can create complex, vortex-antivortex pairs (that exhibit smoothly varying ferroelectric polarization with a 10 nm periodicity) that are reminiscent of topological features such as skyrmions and merons. The key role of a combination of advanced layer-by-layer growth techniques, atomic-resolution mapping of structure and local polar distortions using scanning-transmission electron microscopy, xray spectromicroscopy and phase-field modeling approaches will be discussed. Finally, the implications of these observations are discussed as they pertain to producing new states of matter and emergent phenomena (such as chirality) in such superlattices. I will finish up by spending some time on the broader context of oxide superlattices.

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Magnetic skyrmions in multilayer materials: Static phase diagram and controlled nucleation (Invited)

F Büttner[1], I Lemesh[1], M Schneider[2], B Pfau[2], C Günther[3], P Hessing[2], J Geilhufe[2], L Caretta[1], D Engel[2], B Krüger[4], J Viefhaus[5], S Eisebitt[2,3] and G Beach[1]

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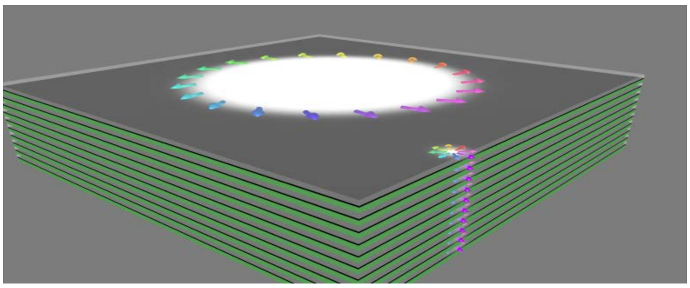
Skyrmions are domains in perpendicular magnetic materials. Their defining property is a spherical topology, which in practical terms means that skyrmions are enclosed by a defectfree closed-loop domain wall. Typically, skyrmions are circular. Skyrmions are the smallest non-trivial entities in magnetism and therefore constitute the most promising way to encode information in next generation magnetic data storage devices.

The properties of skyrmions derive from the parameters of the host magnetic material. Those parameters can be most easily tuned using multilayer materials of alternating layers of transition metal ferromagnets and non-magnetic spacers with large spin orbit interaction. However, tailoring skyrmion properties has proven difficult because a coherent theory that would predict the correlation between material parameters and skyrmion properties did not exist until recently. Also, even if a material is known to host skyrmions in principle, it is not trivial to create them. In particular, integrating a method for deterministic creation of single skyrmions at controlled locations into actual devices has remained a challenge.

In this talk, I will present our novel theoretical model that analytically describes the energy of isolated skyrmion in multilayer materials of arbitrary thickness. Due to its analytical nature, the model evaluates extremely fast and allowed us to discover a variety of new skyrmion phases. Those phase include energy landscapes with multiple minima, leading to skyrmions with zero stiffness or to a coexistence of two completely different types of skyrmions, as illustrated in Fig. 1. Excellent agreement of our predictions with micromagnetic simulations could be verified [1]. Experimentally, we demonstrate a simple method to deterministically nucleate skyrmions by spin orbit torque pulses. I will provide a detailed explanation of the nucleation mechanism and discuss how it can be integrated into actual devices [2].



[1] Büttner, F., Lemesh, I. & Beach, G. S. D. Full phase diagram of isolated skyrmions in a ferromagnet. arXiv:1704.08489 (2017).

[2] Büttner, F. et al. Field-free deterministic ultra fast creation of skyrmions by spin orbit torques. arXiv:1705.01927 (2017).

Magnetic skyrmions in ultrathin Fe films induced by hydrogenation (Invited)

R Wiesendanger and P Hsu

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Based on the discovery of nanoscale magnetic skyrmion lattices [1] as well as individual skyrmions [2] in ultrathin magnetic films and bilayers, stabilized by interfacial Dzyaloshinskii-Moriya interactions, applications of magnetic skyrmions for future spintronic devices, such as memory and logic elements, have become feasible [3]. The properties of magnetic skyrmions can widely be tuned, e.g. by multiple interface engineering, leading to skyrmionic states in metallic multilayer systems being stable up to room temperature [4-6] and in zero magnetic field. Alternatively, chemical treatments, e.g. by oxidation or hydrogenation of ultrathin magnetic thin films can serve as a simple route towards tailored skyrmionic states.

Here, we report on the emergence of individual nanoscale magnetic skyrmions as well as dense skyrmionic lattices by dosing atomic hydrogen onto ultrathin Fe films grown on Ir(111). Previously, a spin spiral ground state was found for the pseudomorphic strained Fe double-layer (DL) on Ir(111) with a rather short period of about 1.3 nm, which could not be transformed into a skyrmionic state in an external magnetic out-of-plane field of up to 9 T [7]. After dosing atomic hydrogen, the pseudomorphic strained Fe-DL forms a p(2x2) superstructure, accompanied by a spin spiral ground state with an enlarged period of up to 4.0 nm, as observed by spin-polarized scanning tunneling microscopy (SP-STM) [8]. In contrast to the absence of a magnetic phase transition for the pure ultrathin Fe film on Ir(111), field-dependent SP-STM measurements on the hydrogenated Fe-DL show a transition to axially symmetric magnetic skyrmions with a diameter of 3 - 4 nm only. The unique rotational sense of these skyrmions is confirmed by vector-resolved SP-STM studies [2,9]

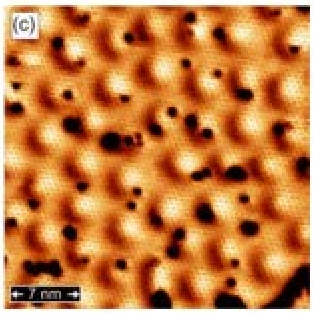

Figure 1: Nanoscale magnetic skyrmions observed in hydrogenated ultrathin Fe films on Ir.

[1] S. Heinze et al., Nature Physics 7, 713 (2011).
[2] N. Romming et al., Science 341, 6146 (2013).
[3] R. Wiesendanger, Nature Reviews Materials 1, 16044 (2016).
[4] G. Chen et al., Appl. Phys. Lett. 106, 242404 (2015).
[5] C. Moreau-Luchaire et al., Nature Nanotechnol. 11, 444 (2016).
[6] S. Woo et al., Nature Mater. 15, 501 (2016).
[7] P.-J. Hsu et al., Phys. Rev. Lett. 116, 017201 (2016).
[8] R. Wiesendanger, Rev. Mod. Phys. 81, 1495 (2009).
[9] N. Romming et al., Phys. Rev. Lett. 114, 177203 (2015).

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Topological magnetic defects in helimagnetic FeGe

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Complex spin textures, like helical spin spirals with a fixed wavelength, can occur due to chiral magnetic interactions. Chiral magnets are a striking nanoscopic analog to liquid crystals, possessing lamellar phases and ordered topological defects. Defects are of great importance as they strongly influence order and mobility of the spin system. Here we present the experimental observation with the combination of micromagnetic simulations of such 1D and 2D objects with non-trivial topology in the helimagnetic phase of FeGe using magnetic force microscopy. We show that the depinning and subsequent motion of edge dislocation govern the local magnetization dynamics. Moreover, the defects can form chains and build topological domain walls, which are distinctly different from classical antiferro- and ferromagnets. Experimentally, three main types of domain walls are found depending on the angle between neighboring domain orientations. In contrast to conventional ferroics, the domain walls exhibit a well-defined inner structure, which - analogous to cholesteric liquid crystals - consists of topological disclination and dislocation defects. Similar to the magnetic skyrmions that form in the same material the domain walls can carry a finite skyrmion charge, permitting an efficient coupling to spin currents and contributions to a topological Hall effect. Thus, going beyond skyrmions, chiral magnets reveal a new family of magnetic nano-objects with non-trivial topology.

Study of domain walls in bulk bismuth ferrite at atomic level (Invited)

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In multiferroic bismuth ferrite (BiFeO3), the domain walls (DWs) have properties that are fundamentally different from those of the bulk. It was shown that the DWs in BiFeO3 thin films and bulk ceramic possess higher electrical conductivity than the domain interiors [1,2]. Mobile charged defects, accumulated at the DWs to screen polarization charges, have been proposed as the origin of DW local conduction, however, the presence of defects has not yet been directly confirmed.

In this talk a direct evidence of the accumulation of charged defects at DWs in BiFeO3 using aberration corrected electron microscopy will be discussed. We proposed that in addition to electrostatic forces, the lattice strain at DWs may also drive the defects towards the DW region. With two analytical methods (Electron energy loss spectroscopy and quantitative High-angle annular dark-field imaging) iron (IV) ions and bismuth vacancies were identified at the DWs. Iron (IV) ions in BiFeO3 are associated with electron holes that lead to p-type hopping conduction at the domain walls. We will show that the resulting p-type hopping conductivity at DWs can be tailored by material processing conditions [3] thus advancing the engineering of local conductivity in ferroelectrics.

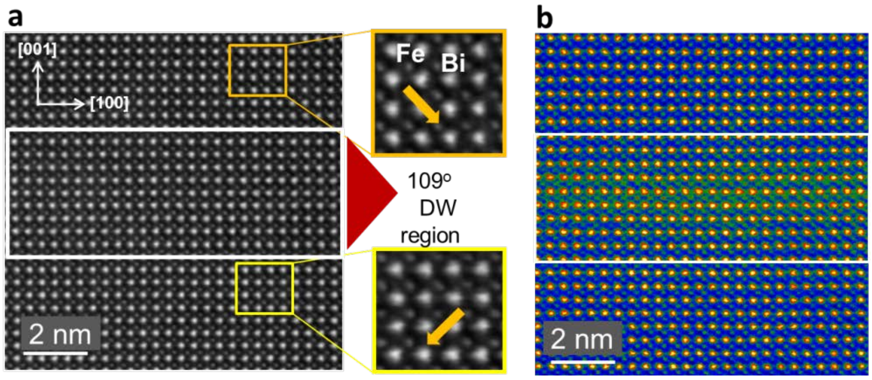

Fig.1: HAADF-STEM image of 109° DW in [010] zone axis with indicated DW region and Fe displacements in the two adjacent domains (arrows in the insets) (a) with the corresponding LAADF-STEM image where the contrast indicates lattice strain gradient across the DW region (b) [3].

[1] J. Seidel et al., Nature Materials 8 (2009).
[2] T. Rojac et al., Adv. Funct. Mater. 25 (2015).
[3] T. Rojac et al., Nature Materials 16 (2017).

Magnon spectrum of the skyrmion-host I nsulator Cu_2OSeO_3

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Complex low-temperature-ordered states in chiral magnets are typically governed by a competition between multiple magnetic interactions. In chiral helimagnets, the spiral structure results from the presence of antisymmetric Dzyaloshinskii-Moriya interactions that twist the otherwise ferromagnetic spin arrangement. The long-range order of topologically stable spin vortices known as skyrmions has been established in a number of such compounds, most famously in the metallic MnSi. The chiral-lattice multiferroic Cu_2OSeO_3 became the first insulating helimagnetic material in which a skyrmion-lattice type of order was established. In our recently published work [Nature Comm. 7, 10725 (2016)], we employed state-of-the-art inelastic neutron scattering to comprehend the full three-dimensional spin-excitation spectrum of Cu_2OSeO_3 over a broad range of energies in the spin-spiral state. We observed distinct types of high- and low-energy dispersive magnon modes separated by an extensive energy gap in excellent agreement with the previously suggested microscopic theory based on a model of entangled Cu4 tetrahedra. The comparison of our neutron spectroscopy data with model spin-dynamical calculations based on these theoretical proposals enables an accurate quantitative verification of the fundamental magnetic interactions in Cu_2OSeO_3 that are essential for understanding its abundant low-temperature magnetically ordered phases. To a good approximation, the spectrum of Cu_2OSeO_3 can be reproduced using a Hamiltonian with only five Heisenberg exchange parameters, neglecting the antisymmetric terms. More recently, however, we also observed signatures of the Dzyaloshinskii-Moriya coupling in the magnon spectrum of Cu_2OSeO_3, despite their smallness as compared to the Heisenberg exchange interactions. We discuss how the observed spin gaps resulting from the antisymmetric exchange terms could be possibly used to experimentally measure the direction of the Dzyaloshinskii-Moriya vectors that are part of the magnetic Hamiltonian of chiral helimagnets.

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Perpendicular exchange bias and bubble domains in Pt/Co/IrMn

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In thin film systems with broken inversion symmetry, the Dzyaloshinskii-Moriya interaction (DMI) influences the field- or current-driven magnetic switching and domain wall (DW) motion by setting the chirality of magnetic textures [1-3]. In this work, we sputter-deposited polycrystalline and epitaxial layers of Pt/Co/Ir20Mn80 exhibiting perpendicular magnetic anisotropy and a perpendicular exchange bias (~100 mT). These multilayers are potentially of interest because of the coincidence of the DMI with a vertical exchange field that could remove the need for an externally applied field to stabilise skyrmion bubbles.

We have measured the exchange bias in SiO2/Ta(5)/Pt(2)/Co(tCo)/IrMn(tIrMn)/Pt(3) and Al2O3/Pt(3)/Co(tCo)/IrMn(tIrMn)/Pt(5) stacks (thickness in nm) as a function of the layer thickness of both Co (tCo = 0.2-2 nm) and IrMn (tIrMn = 1-10 nm) layers (Fig. 1). We were also able to engineer the blocking temperature of the IrMn and bring it below room temperature for sufficiently thin layers (Fig. 2). Wide-field Kerr microscopy showed that the DWs turn from smooth to rough at the onset of the exchange bias.

To investigate the DMI, we measured the asymmetric bubble expansion under an in-plane field, which lifts the energy degeneracy of DWs [2-4]. For the epitaxial case, we find that, while the DW velocity increases for in-plane fields parallel to the direction of the DW motion, it is suppressed for anti-parallel in-plane fields. This behaviour does not fit to the modified domain wall creep model [4] and requires an understanding of the Co/IrMn interface in this system.

We also compare the results with polycrystalline layers of Pt/Co/FeMn which has exhibits a lower exchange field, and attains perpendicular anisotropy for a narrower range of Co layer thickness.

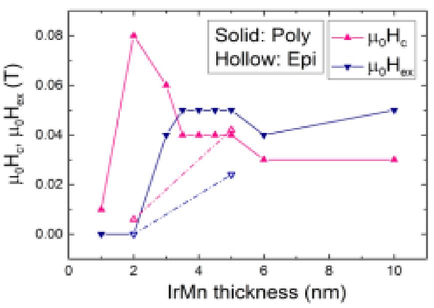

Figure 1: Coercivity H_c and exchange field H_{ex} in Pt(5 nm)/Co(1 nm)/IrMn(t_{IrMn}).

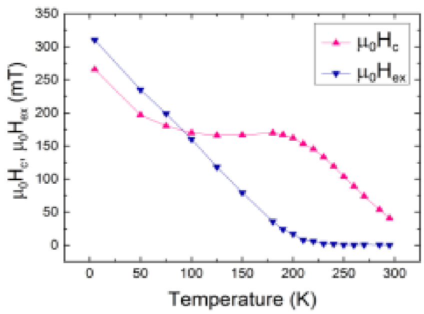

Figure 2: Coercivity H_c and exchange field H_{ex} in Pt(3 nm)/Co(1 nm)/IrMn(2 nm) as a function of temperature.

[1] Emori S. et al., Nature Materials 9, 611-616 (2013).
[2] Hrabec A. et al., Phys. Rev. B 90, 020402(R) (2014).
[3] Wells A. et al., Phys. Rev. B 95, 054428 (2017).
[4] Je S.-G. et al., Phys. Rev. B 88, 214410 (2013).

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Skyrmion stability and hall effect (Invited)

O Tretiakov

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Manipulating by current small spin textures that can serve as bits of information is one of the main challenges in the field of spintronics. Ferromagnetic skyrmions attracted a lot of attention because they are small in size, better than domain walls at avoiding pinning sites, and move very fast in ferromagnet/heavy-metal bilayers due to spin-orbit torques. I will formulate the microscopic theory of these torques with disorder and calculate the skyrmion Hall angle [1], which was recently revealed by X-ray microscopy [2]. We show that this angle depends on dynamical deformations of the skyrmion due to spin-orbit torques. This theory is rather general and can be extended to describe transport in antiferromagnet/heavy-metal, ferromagnet/topological-insulator, and other bilayers.

Meanwhile, the ferromagnetic skyrmions also have certain disadvantages to employ them in spintronic devices, such as the presence of stray fields and transverse to current dynamics. To avoid these unwanted effects, we propose a novel topological object: the antiferromagnetic skyrmion [3]. This topological texture has no stray fields and its dynamics are faster compared to its ferromagnetic analogue [3,4]. More importantly, I will show that due to unusual topology it experiences no skyrmion Hall effect, and thus is a better candidate for spintronic applications. Furthermore, I will discuss the stability of both antiferromagnetic and ferromagnetic skyrmions at finite temperatures.

[1] I. Ado, O. A. Tretiakov, and M. Titov, Phys. Rev. B 95, 094401 (2017).
[2] K. Litzius, I. Lemesh, B. Kruger, P. Bassirian, L. Caretta, K. Richter, F. Buttner, K. Sato, O. A. Tretiakov, J. Forster, R. M. Reeve, M. Weigand, I. Bykova, H. Stoll, G. Schutz, G. S. D. Beach, and M. Klaui, Nature Physics 13, 170 (2017).
[3] J. Barker and O.A. Tretiakov, Phys. Rev. Lett, 116, 147203 (2016).
[4] D. R. Rodrigues, K. Everschor-Sitte, O. A. Tretiakov, J. Sinova, and Ar. Abanov, Phys. Rev. B 95, 174408 (2017).

Transport properties of antiferromagnetic chiral textures (Invited)

P Buhl, F Freimuth, S Blügel and Y Mokrousov

Peter Grünberg Institut and Institute for Advanced Simulation, Germany

The antiferromagnetic (AFM) chiral textures such as domain walls and skyrmions are rapidly entering the world of spinorbitronics and skyrmionics owing to the bright prospects associated with their utter robustness and operation speed. In my talk I will review our recent advances in theoretical understanding and modeling of spin transport properties of antiferromagnetic skyrmions [1]. In contrast to ferromagnetic skyrmions [2], the semiclassical “adiabatic” framework in antiferromagnets becomes rather intricate owing to the generally more complex gauge symmetry of these systems. To overcome this difficulty we developed an advanced and powerful density functional theory (DFT) based methodology for computing the transport properties of AFM textures. Within this approach, based on the DFT description of collinear AFM materials, we employ the Boltzmann formalism together with real-space real-time evolution of electrons in AFM textures to compute the currents arising in response to an electric field. By considering skyrmionic AFM textures in selected “synthetic” and “intrinsic” antiferromagnets we uncover the emergence of pronounced pure transversal spin currents, and we suggest that the corresponding topological spin Hall effect could be used not only to detect the AFM skyrmions, but also to possibly employ them as spin current generators in AFM-based devices [1]. We scrutinize the sensitivity of the topological spin Hall effect with respect to the details of the electronic structure and skyrmion shape, suggesting that the magnitude and sign of the novel phenomenon can be engineered by tuning such system’s parameters as thickness, band filling, and magnetic exchange parameters. We also explore the possibility that the properties of the spin currents AFM textures give rise to could be used to experimentally distinguish between distinctly different topological classes of corresponding chiral particles. Besides being an important step in our understanding of the topological properties of ever more complex skyrmionic systems, our results bear great potential in putting chiral antiferromagnets on the track of skyrmionics.

[1] P. M. Buhl, et al., Phys. Status Solidi RRL 11, 1700007 (2017).
[2] C. Franz, et al., Phys. Rev. Lett. 112, 186601 (2014).

Robust metastable skyrmions in bulk chiral magnet (Invited)

Y Taguchi[1], K Karube[1], J White[2], X. Z. Yu[1], D Morikawa[1], A Kikkawa[1], H Oike[1], F Kagawa[1], N Reynolds[2], J Gavilano[2], Y Tokunaga[3], H Rønnow[4] and Y Tokura[1,5]

[1]RIKEN Center for Emergent Matter Science (CEMS), Japan, [2]Paul Scherrer Institute (PSI), Switzerland, [3]University of Tokyo, Japan, [4]Institute of Physics, Switzerland, [5]University of Tokyo, Japan

Skyrmions have recently attracted much attention as they exhibit various kinds of emergent phenomena and also they are expected to be applied to spintronics devices. The formation of skyrjmions are known to occur both at hetero-interface and in bulk chiral or polar magnets, with broken inversion symmetry. However, chiral magnets have been known to host skyrmions only below room temperature thus far, and their variations are limited to a few classes of materials, such as B20-type alloys (e.g., MnSi). Recently, we found a new class of cubic chiral magnets, b-Mn-type Co-Zn-Mn alloys that exhibit skyrmion crystal state at and above room temperature [1]. In addition to the thermodynamically equilibrium state, metastable skyrmion crystal state was also observed by field cooling process, and the metastable skyrimion crystal prevails in a wide region of temperature and magnetic-field [2]. Furthermore, within the metastable state, the skrymion lattice undergoes a transformation from triangular lattice to a square lattice at low temperatures [2].

[1] Y. Tokunaga et al., Nature Commun. 6: 7638 (2015)
[2] K. Karube, J. S. White et al., Nature Mat. 15, 1237 (2016)

Tuning domain wall energy in perpendicular magnetic thin films (Invited)

P Shepley

University of Leeds, United Kingdom

The energy of domain walls in thin films with perpendicular magnetic anisotropy is a balance between competing energies. Interface properties like surface anisotropy and the interfacial Dzyaloshinskii-Moriya (DM) interaction become important in ultra-thin multilayer films, while properties associated with bulk, such as volume anisotropy and exchange stiffness, continue to play a role. Controlling these properties to tune the domain wall energy gives us an understanding of how domain walls will behave in logic or data storage devices.

I'll talk about how we can use different parameters, including layer thickness, interface quality and externally applied strain to access different contributions to the domain wall energy. I'll focus on the energy of magnetic domain walls in perpendicularly magnetised Pt/Co/Ir thin films. By measuring the magnetic anisotropy, exchange stiffness and DM interaction, we can calculate the domain wall energy for thin films with a range of Co thickness. Applying external strain to the Pt/Co/Ir films using piezoelectric transducers modifies the magnetic anisotropy and increases the creep velocity of domain walls [1]. I'll show that the changes in domain wall energy are a good predictor of the size of the changes to domain wall velocity across a range of film thicknesses [2] (see Figure 1). Designing thin film systems whose properties give low domain wall energies (i.e. materials which balance low magnetic anisotropy energy, low exchange stiffness, and higher DM interaction) will optimise the piezoelectric strain control of domain walls in new devices.

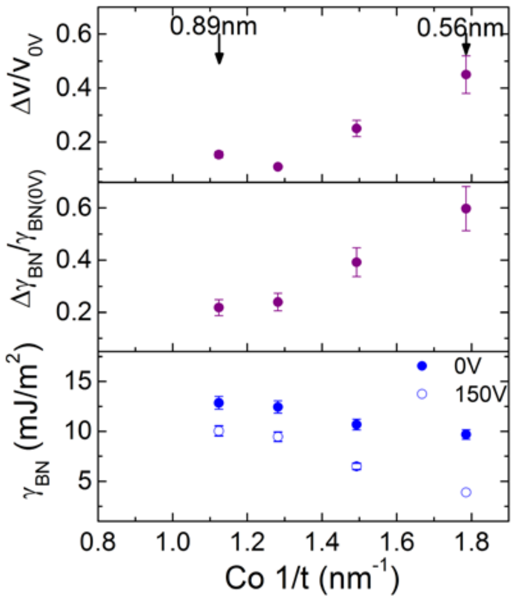


Figure 1. The proportional change in domain wall creep velocity under 0.1% strain, the proportional change in domain wall energy due to 0.1% strain and the domain wall energy in unstrained (0V) and 0.1% strained (150V) Pt/Co(t)/Ir are plotted against the inverse of Co thickness 1/t.

[1] P. M. Shepley, A. W. Rushforth, M. Wang, G. Burnell, T. A. Moore. Scientific Reports. 5, 7921 (2015).

[2] P.M. Shepley, H. Tunnicliffe, K. Shahbazi, G. Burnell, T.A. Moore. arXiv:1703.05749 (2017)

Optical Creation of 3- and 4-dimensional Supercrystals (Invited)

V Gopalan[1], V Stoica[2], N Laanait[1], Y Yuan[1], Z Hong[1], Z Zhang[1], S. Lei[3], J Karapetrova[4], A Yadav[4], M McCarter[4], A Damodaran[1], G Stone[4], X Zhang[1], L Chen[4], L Martin[4] , R Ramesh[3], H Wen[3] and J Freeland[1]

[1]Pennsylvania State University, USA, [2]Oak Ridge National Laboratory, USA, [3]Argonne National Laboratory, USA, [4]University of California, USA

Non-equilibrium control of novel materials with impulsive excitations has been explored for many decades, yet the large majority of the work has been focused on collapsing an ordered phase into a disordered one. Systems where a new order is created following an impulsive non-equilibrium excitation (e.g. a light pulse) are much less common. To expand the number of systems where we can access new states with non-equilibrium perturbation at room temperature or above, we need to explore the key ingredients for their creation. In this talk, I will discuss the creation of a 3-dimensional supercrystal phase with nanoscale periodicity at and above room temperature using non-equilibrium optical excitation of an oxide heterostructure of $(PbTiO_3)_n/(SrTiO_3)_n$ (PTO-STO). Using above band-gap excitation of ferroelectric superlattices, we are able to convert the mesoscale stripe order of vortex and collinear domains into this new state with a long-range ordering 27.5 nm x 29.5 nm x 25.1 nm periodicity. Importantly, such a phase is not accessible via the equilibrium phase diagram, but can be reversibly written and erased only using light pulses. Experiment and modeling show that interlayer coupling between PTO and STO layers transforms from weak to strong after optical conversion assisted by activated electric and elastic interactions. Furthermore, we determine that the mesoscale strain is dramatically reduced and structural coherency is substantially enhanced in this emergent nanoscale phase created by a non-equilibrium approach.

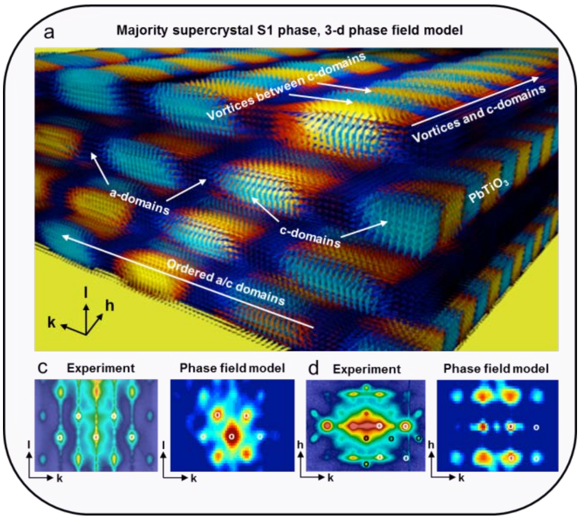


Figure 1 Revealing the structure of the supercrystal. a) Phase field model of calculated 3-d polar structure of majority supercrystal phase. Comparison of diffracted pattern symmetry observed in experiments with the FFT of a KL, b) and HK, c) planes of the model structure. White circles in b) and c) mark the correspondence of experimental RSM and FFT patterns. Black dots from experiment in c) mark satellite reflections attributed to 4-d minority supercrystal phase, while experimental satellite reflections marked by white dots in b) and c) are attributed to both 4-d minority and 3-d majority phase supercrystals.

Wednesday 9 August 2017

Transversal transport coefficients and topological properties (Keynote)

I Mertig

Martin Luther University Halle, Germany

Spintronics is an emerging field in which both charge and spin degrees of freedom of electrons are utilized for transport. Most of the spintronic effects—like giant and tunnel magnetoresistance—are based on spin-polarized currents which show up in magnetic materials; these are already widely used in information technology and in data storage devices.

The next generation of spintronic effects is based on spin currents which occur in metals as well as in insulators, in particular in topologically nontrivial materials. Spin currents are a response to an external stimulus—for example electric field or temperature gradient—and they are always related to the spin-orbit interaction. They offer the possibility for future low energy consumption electronics.

The talk will present a unified picture, based on topological properties, of a whole zoo of transversal transport coefficients: the trio of Hall, Nernst, and quantum Hall effects, all in their conventional, anomalous, and spin flavour. The formation of transversal charge and spin currents as response to longitudinal gradients is discussed. Microscopic insight into all phenomena is presented by means of a quantum mechanical analysis based on the Dirac equation in combination with a semi-classical description which can be very elegantly studied within the concept of Berry curvature.

Conducting domain wall in ferroelectrics: From transport behaviour to precise control for domain-wall based electronics (Invited)

A Kumar

Queens University Belfast, United Kingdom

Domain walls in ferroelectrics are interfaces that separate volumes of differently oriented electrical polarisation. As transition regions, their structural, functional and transport properties have long been expected to differ from domain interiors. Recently, enhanced functionality at the walls has catalysed researchers to look domain walls afresh. In particular, enhanced domain wall conductivity reported in a range of ferroelectric materials has projected them as distinct pseudo 2D functional materials. Since the domains themselves are comparatively insulating, domain walls represent isolated conducting channels which confine currents into narrow sheets. The walls themselves can be created, destroyed or moved upon application of external stimuli and thus could be actively and dynamically deployed for nano-circuitry and reconfigurable domain-wall based nanoelectronics devices. Unfortunately, mechanisms associated with domain wall conduction are not yet clear. Key carrier information such as carrier types, densities and effective masses are still to be determined and transport mechanism are matter of open debate. In addition, a large number of the ferroelectrics where charged domain walls showing significant conduction have been reported are improper ferroelectrics where precise injection and controlled motion of long conductive walls presents another significant challenge. This talk will focus on addressing these key challenges related to domain wall conduction in ferroelectrics. A novel approach employing hall effect in charged conducting ferroelectric domain walls [1] to detect carrier type and densities in ytterbium manganite single crystals will be discussed. The studies suggest that the p-type conduction occurs in the tail-to-tail charged domain walls and carrier densities are about four orders of magnitude below that required for complete screening of polar discontinuity. The observation, mechanical injection and controlled movement of charged conducting domain walls in the improper ferroelastic-ferroelectric Cu3B7O13Cl will be discussed. Walls are straight, tens of microns long, and exist as a consequence of elastic compatibility conditions between specific domain pairs [2]. It will be shown that site-specific injection of conducting walls of up to hundreds of microns in length can be achieved through locally applied point-stress and, once created, that they can be moved and repositioned using applied electric fields, thus satisfying a key requirement for domain wall-based nanocircuitry. The use of localised stress as an external stimulus in conjunction with electric fields to achieve deterministic and reversible control of ferroelectric phase populations (and conductivity associated with arising phase boundaries) in mixed phase bismuth ferrite films will be discussed. Conductive atomic force microscopy reveals significantly enhanced conduction in pressure written regions which correlates with large interfacial strains between phases. Dual reversible control employing electrical bias and nanoscale stress has been employed towards creating a piezo-resitive device exhibiting a maximum current modulation ratio (Ion/Ioff) of upto six orders of magnitude. Such combinatorial manipulations of mixed phase systems via localised stress as discussed here could have broader implications for tuning their conductive and overall functional behaviour.

[1] Campbell et al., Nat. Comm. 7, 13764 (2016).
[2] McQuaid et al., Nat. Comm. 8, 15105 (2017).

Nanoscale Bubble Domains and Topological Transitions in Ultrathin Ferroelectric Films

Q Zhang[1], L Xie[2,3], G Liu[1], S Prokhorenko[4], Y Nahas[3.4], X Pan[3], L Bellaiche[4], A Gruverman[5] and N Valanoor[1]

[1]The University of New South Wales, Australia, [2]Nanjing University, China, [3]University of California, USA, [4]University of Arkansas, USA,[5]University of Nebraska, USA

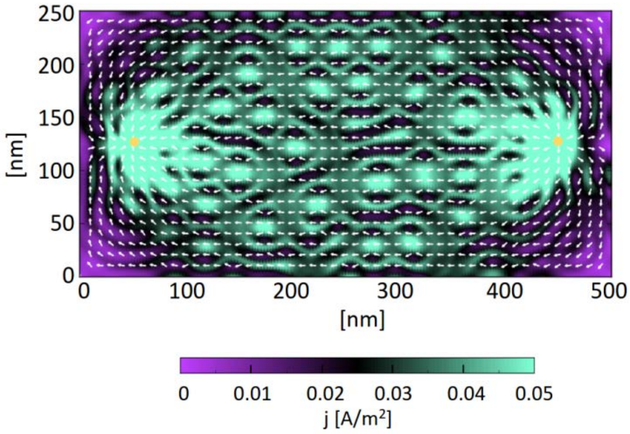
We report the direct observation of nanoscale “bubble domains” in ultrathin epitaxial $PbZr_{0.2}Ti_{0.8}O_3$/SrTiO3/$PbZr_{0.2}Ti_{0.8}O_3$ ferroelectric sandwich structures. They are laterally confined spheroids of sub-10 nm size with local dipoles self-aligned in a direction opposite to the macroscopic polarization of a surrounding ferroelectric matrix. The bubble domains appear due to the competition between incomplete polarization screening (electrostatic) and compressive mechanical strain (elastic) parameters. The existence of the bubble domains is revealed by high-resolution piezoresponse force microscopy (PFM), and is corroborated by aberration-corrected atomic-resolution scanning transmission electron microscopy mapping of the polarization displacements. An incommensurate phase and symmetry breaking is found within these domains, which result in local polarization rotation and hence impart a mixed Néel-Bloch-like character to the bubble domain walls. Moreover, local PFM spectroscopic testing of the bubble domains reveals an electromechanical response twice as large as that of a reference PZT film without bubble domains. Our observations are in agreement with ab-initio-based calculations, which reveal a very narrow window of electrical and elastic parameters that allow the existence of bubble domains. The findings highlight the richness of polar topologies that may develop in ultrathin ferroelectric structures and bring forward the prospect of emergent electronic functionalities due to topological transitions.

Skyrmion gas manipulation for unconventional computing (Invited)

D Pinna[1], J Grollier[2] and K Everschor-Sitte[1]

[1]Johannes Gutenberg Universität Mainz, Germany, [2]Université Paris-Saclay, France,

The topologically protected magnetic spin configurations known as skyrmions offer promising applications due to their stability, mobility and localization. In this work, we emphasize how to leverage the 2-dimensional mobility of an ensemble of such particles to perform computing tasks. In this vein we will present two examples. In the first, we propose a device employing a skyrmion gas to reshuffle a random signal into an uncorrelated copy of itself. This is demonstrated by modelling the ensemble dynamics in a collective coordinate approach where skyrmion-skyrmion and skyrmion-boundary interactions are accounted for phenomenologically. Numerical results are used to develop a proof-of-concept for an energy efficient (~μW) device with a low area imprint (~μm2) capable of enabling future scalable implementations of stochastic computing circuits. The second example will consist of a skyrmion network embedded in a frustrated magnetic film to be used as a suitable physical implementation for reservoir computing applications.The significant key ingredient of such a network is a two-terminal device with non-linear voltage character-istics originating from single-layer magnetoresistive effects, like the anisotropic magnetoresistance or the recently discovered non-collinear magnetoresistance. In order to characterize how such a skyrmion-based system would function, we simulate and analyze i) the current flow through a single magnetic skyrmion due to the anisotropic magneto-resistive effectand ii) the combined physics of local pinning and the anisotropic magneto-resistive effects.



Caption Figure 1: Diagram of the skyrmionic signal reshuffler.

Non-Ising and chiral ferroelectric domain walls: Insights from nonlinear optical microscopy

S Cherifi-Hertel[1], H Bulou[1], R Hertel[1], G Taupier[1], K Dorkenoo[1], C Andreas[1], J Guyonnet[2], I Gaponenko[2], K Gallo[1] and P Paruch[2]

[1]Université de Strasbourg, France, [2]University of Geneva, Switzerland, [3]Royal Institute of Technology, Sweden

The properties of ferroelectric domain walls can significantly differ from those of their parent material. Elucidating their internal structure is essential for the design of advanced devices exploiting nanoscale ferroicity and localized functional properties. Second-harmonic generation (SHG) microscopy allows for the non-perturbative observation of ferroelectric domains and domain walls. The method can provide important insight into the structure of domain walls since the optical susceptibility tensor describing the SHG process is directly related to the local crystal symmetry and to the ferroic order.

We use SHG microscopy to probe the internal structure of 180° ferroelectric domain walls in lead zirconate titanate thin films and lithium tantalate bulk crystals.[1] In both systems we detect a pronounced SHG signal at the walls. Local polarimetry analysis of this signal combined with numerical modeling reveals the existence of a planar polarization within the walls, with Néel and Bloch-like configurations in lead zirconate titanate and lithium tantalate, respectively. Depth-resolved SHG microscopy is employed to analyze the three-dimensional domain wall structure in the lithium tantalate bulk crystal. We thereby find that the chirality of Bloch-type walls may change at line defects, in close analogy to Bloch lines in ferromagnets.

Our results demonstrate a clear deviation from the ideal Ising-type domain wall configuration that is traditionally expected in uniaxial ferroelectrics. This corroborates recent theoretical predictions of a more complex, often chiral domain wall structure.

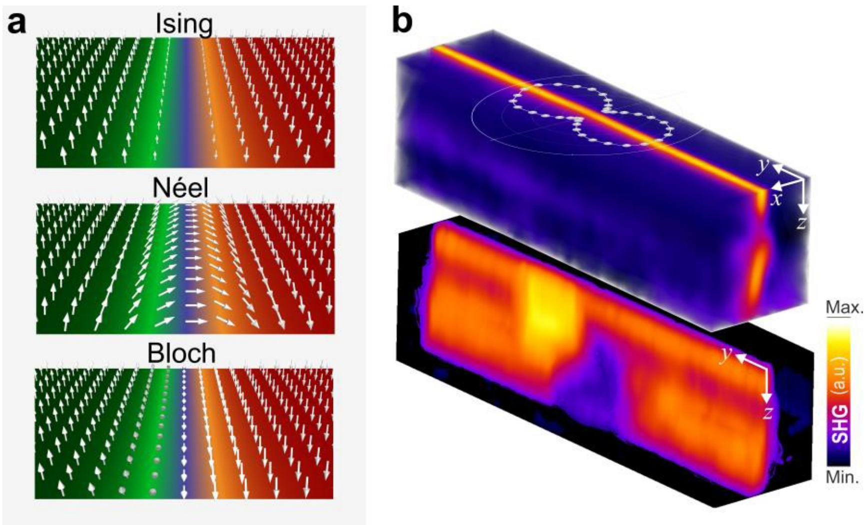


Figure 1. (a) Polar structure at 180° domain walls with Ising, Néel, or Bloch type configurations; (b) Chiral Bloch wall revealed by means of three-dimensional SHG microscopy and polarimetry in periodically poled lithium tantalate.

Domain walls in LiNbO3 single crystals: Controlling conductivity through geometry (Invited)

A Haußmann[1], C Godau[1], T Kämpfe[1], B Wolba[1], A Pawlik[2], A Koitzsch[2], L Kirsten[1], E Koch[1], and L Eng[1]

[1]Technische Universität Dresden, Germany, [2]Leibniz Institute for Solid State and Materials Research Dresden, Germany

In this talk, we will demonstrate that single crystals of a standard ferroelectric material LiNbO3 (LNO) are indeed versatile platforms for the investigation of domain wall (DW) related functio¬nali¬ties such as nanoscale-confined electrical DW conductivity. Measurements of this property were carried out both using c-AFM and macroscopic electrodes in a sample thickness range from 100 nm (exfoliated thin single crystalline sheets) up to 500 µm (industry-grade single crystals). Furthermore, the contact-free characterisation of the charge carrier distribution in the vicinity of DWs proved feasible through photoelectron emission microscopy (PEEM) [1]. These investi¬ga¬tions are complemented by optical 3D DW tracking using two novel techniques, i.e. Cherenkov second harmonic generation microscopy (CSHGM) [2] and optical coherence tomography (OCT) [3], that allow fingerprinting both the DW static and dynamical behaviour.

Within our studies, we inspect DWs grown by standard high-field electrical poling, exhibiting small head-to-head inclinations (< 0.5°) with respect to the polar axis as well as DWs purposely tuned for inclinations as high as 6° [2], which increases the DW conductivity by 3-4 orders of magnitude. Also more complex DW topologies were prepared applying a special heat treatment, with DWs then covering the full range of inclinations from -90° to +90°. Finally, we show that a consistent interpretation of our c-AFM results is possible through modelling the conductivity landscape of a DW by a random resistor network, based on the geometrical data as obtained by CSHGM [4].Aspects of chiral soliton dynamics in disordered thin films:

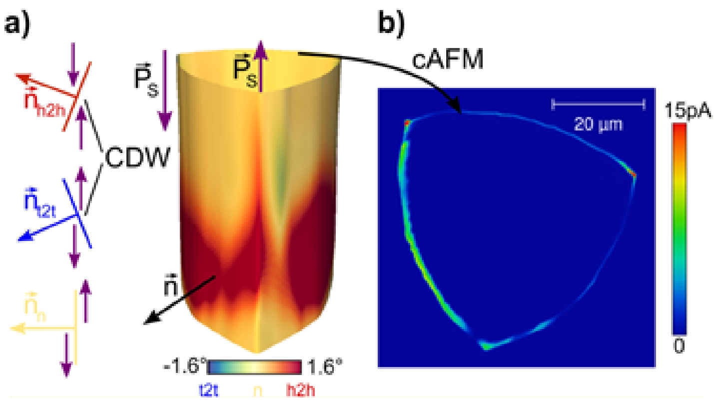


Figure 1:
(a) Inclination profile of a DW as reconstructed from CSHGM data; (b) corresponding c-AFM image measured at the top z surface with a +10 V bias.

[1] A.-S. Pawlik, T. Kämpfe, A. Haußmann, T. Woike, U. Treske, M. Knupfer, B. Büchner, E. Soergel, R. Streubel, A. Koitzsch and L. M. Eng, Nanoscale (2017), accepted.

[2] C. Godau, T. Kämpfe, A. Thiessen, L.M. Eng, and A. Haußmann, ACS Nano 11 (2017) 4816.

[3] A. Haußmann, L. Kirsten, S. Schmidt, P. Cimalla, L. Wehmeier, E. Koch, and L.M. Eng, Ann. Phys. (2017) in print.

[4] B. Wolba, J. Seidel, C. Cazorla, C. Godau, A. Haußmann, and L.M. Eng, Adv. Electron. Mater. (2017) submitted.

Domain wall creep and current-driven skyrmion motion (Invited)

J Kim

Université Paris-Saclay, France

Chiral spin states such as Néel domain walls [1,2] and skyrmions [3,4] have been the focus of much recent attention because of their strong potential for information storage and processing. Of particular interest are ultrathin ferromagnetic films, such as nm-thick cobalt on platinum, where a chiral Dzyaloshinskii-Moriya interaction (DMI) are induced by large spin-orbit coupling in an adjacent buffer layer. A drawback of such materials is that magnetic disorder is often present, which leads to phenomena such as domain wall creep [5]. We will present some recent theoretical studies on how disorder affects the dynamics of chiral solitons such as Néel walls and skyrmions. We will describe some extensions to the creep theory of domain wall motion when DMI is present. We will also discuss how disorder affects current-driven skyrmion motion [6], such as the appearance of an extrinsic skyrmion Hall effect due to defect scattering and velocity versus force curves that resemble thermally-driven domain wall motion.

[1] J.-P. Tetienne et al., Nat. Commun. 6, 6733 (2015).
[2] M. J. Benitez et al., Nat. Commun. 6, 8957 (2015).
[3] C. Moreau-Luchaire et al., Nat. Nanotechnol. 11, 444 (2016).
[4] O. Boulle et al., Nat. Nanotechnol. 11, 449 (2016).
[5] V. Jeudy et al., Phys. Rev. Lett. 117, 057201 (2016).
[6] J.-V. Kim and M.-W. Yoo, Appl. Phys. Lett. 110, 132404 (2017).

Dynamical phenomena of magnetic skyrmions. ~how to create nanometric topological spin textures~ (Invited)

M Mochizuki

Waseda University, Japan

We will report on our recent theoretical studies on dynamical phenomena of magnetic skyrmions in chiral lattice magnets, particularly focusing on how to create nanoscale, topological skyrmion spin textures using external parameters such as electric fields, magnetic fields, lights and heats. This talk consists of the following two topics mainly.

[1]: Skyrmion creation by local application of electric fields

Swirling spin structure of magnetic skyrmion can induce electric polarizations in insulating magnets such as Cu_2OSeO_3 and GaV_4S_8 via relativistic spin-orbit interactions. We theoretically propose that in these multiferroic chiral-lattice magnets, skyrmions can be electrically created on a thin-film specimen within a few nanoseconds by applying an electric field via an electrode tip taking advantage of coupling between noncollinear skyrmion spins and electric polarizations [1,2]. This finding will pave a route to utilizing multiferroic skyrmions as information carriers for low-energy-consuming magnetic storage devices without Joule-heating energy losses.

[2]: Local creation of nanometric skyrmions by global application of external field

It has been theoretically proposed that local applications of external field such as magnetic field, light, and heat within a region comparable to or smaller than a skyrmion size are a possible efficient way to create nanometric skyrmions. However, since it is technically difficult to squeeze their spot size within a nanometric region actually, these methods are rather unrealistic and impractical. To utilize nanometric magnetic skyrmions as information carriers in high-density storage devices, it is necessary to establish a method to create intended number of skyrmions at intended places in a specimen with low energy cost even by global application of external field to entire specimen. We discuss how to overcome this seemingly unsolvable problem.

[1] M. Mochizuki, Advanced Electronic Materials 2, 1500180 (2015).
[2] M. Mochizuki and Y. Watanabe, Applied. Physics Letters 107, 082409 (2015).

Magnetic Imaging of Topological Spin Structure Dynamics due to Spin-Orbit Effects (Invited)

R Reeve[1], K Litzius[1,2,3], I Lemesh[4], B Krüger[1], P Bassirian[1], L Caretta[4], K Richter[1], F Büttner[4], K Sato[5], O Tretiakov[6,7], J Förster[3], M Weigand[3], I Bykova[3], H Stoll[3], G Schütz[3], G Beach[4] and M Kläui[1]

[1]Johannes Gutenberg-University, Germany, [2]Graduate School of Excellence Materials Science in Mainz, Germany, [3]Max Planck Institute for Intelligent Systems, Germany,[4]Massachusetts Institute of Technology, USA, [5]Tohoku University, Japan, [6]Far Eastern Federal University, Russia

In recent years it has emerged that the spin-orbit interaction can lead to a range of novel phenomena which could be highly advantageous for spintronic devices such as magnetic memories and logic [1,2], launching a new field of spin-orbitronics. Firstly spin-orbit interaction underlies the Dzyaloshinskii-Moriya interaction (DMI), which allows for the formation of topological spin configurations exhibiting enhanced stability. Secondly spin orbit effects result in new avenues to generate torques on magnetization and thereby dynamically manipulate magnetic states.

In heavy-metal (HM) /ferromagnet (FM) /oxide systems such as Ta(5nm)/ Co20Fe60B20(1nm)/ MgO(2nm) we investigate magnetization dynamics where the DMI leads to homo-chiral domain walls, which can be efficiently manipulated via the spin-orbit torques (SOTs) which concurrently occur in the system [3, 4]. By combined Kerr imaging and transport characterization we determine the DMI and SOTs. We find that the DMI is critically dependent on interface [3] while the SOT efficiency strongly depends both on the direction of the current flow with respect to the wall, due to the symmetry of the torques and also on the direction of applied fields which compete with the DMI to promote walls with either Bloch or Néel character.

Going beyond domain walls, skyrmions are newly discovered topological magnetic quasi-particles which occur in similar HM/FM/Oxide systems and which offer certain advantages for potential device applications. We are able to demonstrate the room-temperature formation of skyrmions in a "racetrack"-type device [1] and subsequently image their controlled propagation due to SOTs using scanning-transmission x-ray microscopy [5]. Finally, via dynamic time-resolved imaging we are able to map the trajectories of the skyrmions and determine their velocities [6]. We find that the skyrmions move at an angle with respect to the current flow, termed the skyrmion Hall effect. However in contrast to existing models the angle of the motion is found to depend on the skyrmion velocity, showing that the dynamics are more complex than previously thought and to explain the behaviour one needs to take into account skyrmion deformation [6].

[1] S. S. P. Parkin et al., Science 320, 190 (2008).
[2] O. Boulle et al., Mater. Sci. Eng. R 72, 159 (2011).
[3] R. Lo Conte et al., Phys. Rev. B 91, 014433 (2015).
[4] T. Schulz et al., Appl. Phys. Lett. 107, 122405 (2015).
[5] S. Woo et al., Nature Materials 15, 501 (2016).
[6] K. Litzius et al., Nature Physics 13, 170 (2017).

<u>Thursday 10 August 2017</u>

Spin topology in low dimensional magnets (Keynote)

C Panagopoulos

Nanyang Technological University, Singapore

Using particle-like spin structures as a paradigm, I will demonstrate that the states induced by spin orbit coupling and inversion symmetry breaking in magnetic multilayers open a broad perspective with significant impact in the practical technology of spin topology. In particular, I will discuss our effort in Singapore to modulate interfacial properties for functional magnetic skyrmions at room temperature. First, I will introduce a materials platform namely, Ir/Fe/Co/Pt to tune skyrmion size and density, thermodynamic stability parameter, as well as the crossover between isolated and disordered-lattice configurations. Then I will focus on recent results on the nucleation, electrical signature, collective spin excitation modes, current-induced formation and dynamics of sub-100nm skyrmions using complementary transport, thermodynamic and imaging techniques.

Scanning force microscopy manipulation of individual skyrmions (Invited)

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TU Dresden, Germany

In the past years, a lot of interest was spurred by discoveries that established the existence of vortex-like magnetic states, so-called skyrmions, in some helimagnetic compounds characterized by the anisotropic Dzyaloshinskii-Moriya (DM) interaction. Originally introduced in the context of pion fields, the expression skyrmion today is used in a more general sense as a term for a mathematical construct that describes a topologically protected particle-like object. Due to their size and topological nature magnetic skyrmions are discussed as promising novel candidates for elementary magnetic storage units even at room temperature, or as the integral part in novel spintronic applications. Creation, annihilation, and manipulation of single skyrmions thus is key to any such skyrmionic device.

We will show here, that scanning force microscopy (SFM) not only provides real-space mapping of such skyrmions in a variety of materials [1,2,3], but equally provides a valuable tool to reproducibly manipulate single skyrmions. More precisely, we will introduce in how to generate, annihilate, and move an individual skyrmion by the SFM tip. The study here has been carried out in the metastable skyrmion phase in FexCo(1-x)Si (x=0.5) at T = 10 K and B = 16 mT, as shown in fig. 1.

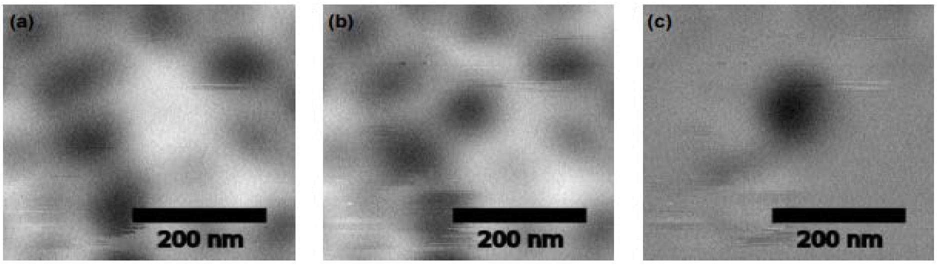

Figure 1. Generation of an individual skyrmion in $Fe_xCo_{(1-x)}Si$ (x=0.5) by using the magnetic stray field of a magnetic force microscope tip in the metastable skyrmion phase. Images (a) and (b) have been recorded before and after manipulation, respectively, while (c) displays the difference image between the two.

[1] Milde, P., Köhler, D., Seidel, J., et al. (2013). Unwinding of a Skyrmion Lattice by Magnetic Monopoles, Science 340, 1076-1080.

[2] Kézsmárki, I., Bordacs, S., Milde, P., et al. (2015). Néel-type skyrmion lattice with confined orientation in the polar magnetic semiconductor GaV4S8, Nature Materials 14, 1116-1123.

[3] Milde, P., Neuber, E., Bauer, A., et al., (2016). Heuristic Description of Magnetoelectricity of Cu2OSeO3, Nano Letters, 16, 5612-5618.

Stabilization, nucleationa and manipulation of radial vortices and skyrmions (Invited)

G Finocchio

University of Messina, Italy

Solitons are very promising for the design of the next generation of ultralow power devices for storage and computation. In particular, Neél skyrmions stabilized by the interfacial Dzyaloshinskii-Moriya Interaction (IDMI) in out-of-plane materials offer a scalability beyond the limit of CMOS technology for storage. However, the interesting aspect of skyrmions is their possible use for ICT devices such as oscillators [1] and detectors[2]. The oscillators can be achieved in the IDMI region parameter where the a dynamical skyrmion is stabilized by a dc spin-polarized current, while the unbiased detectors exhibit sensitivities (output voltage/input power) as larger as 2000V/W. Here, we discuss in details the results of micromagnetic simulations and experiments of different solutions for the realization of skyrmion based microwave oscillators and detectors[3].

In conclusions, our findings show the potential of skyrmions for the development of a skyrmion based technology[4].

The second part of the presentation will focus on the proprieties of radial vortices that can stabilized and manipulated in materials with in-plane easy axis and IDMI. In particular, I will discuss how the IDMI is able to lift the energy degeneracy of a magnetic vortex state by stabilizing a topological soliton with radial chirality. It has a non-integer Skyrmion number S ($0.5 < S < 1$) due to both the vortex core polarity and the magnetization tilting induced by the IDMI boundary conditions.

Micromagnetic simulations predict that a magnetoresistive memory based on the radial vortex state in both free and polarizer layers can be efficiently switched by a threshold current density smaller than 106 Acm-2. The switching processes occur via the nucleation of topologically connected vortices and vortex-antivortex pairs, followed by spin-wave emissions due to vortex-antivortex annihilations.

[1] Carpentieri M., et al, Topological, non-topological and instanton droplets driven by spin-transfer torque in materials with perpendicular magnetic anisotropy and Dzyaloshinskii-Moriya Interaction, Sci. Rep. 5, 16184 (2015).

[2] Finocchio G., et al, Skyrmion based microwave detectors and harvesting, Appl. Phys. Lett. 107, 262401 (2015).

[3] Finocchio G., Zeng Z., et al, in preparation.

[4] Finocchio G., et al, Magnetic skyrmions: from fundamental to applications, J. Phys. D. Appl. Phys. 49, 423001 (2016).

[5] Siracusano G., Tomasello R., et al, Magnetic Radial Vortex Stabilization and Efficient Manipulation Driven by the Dzyaloshinskii-Moriya Interaction and Spin-Transfer Torque, Phys. Rev. Lett. 117, 87204 (2016).

International Workshop on Topological Structures in Ferroic Materials

Quantitative Hall Effect and Electrical Diode characteristics of naturally occurring p-n junctions in Erbium Manganite

P Turner, S McCartan, M Campbell, J McConville, A Kumar and J Gregg

Queen's University Belfast, United Kingdom

The field of ferroelectrics research witnessed a seismic shift when, towards the end of the last decade,Seidel et al presented their seminal work concerning the phenomenon of room temperature domain wall conduction (DWC) in rhombohedral BFO thin films [1]. Ever since, great interest has been invested into exploring the nature of this phenomenon, providing a fertile playground for the advancement of our understanding.

In recent years, hexagonal manganites, demonstrating improper ferroelectricity, have been the subject of some interesting discussion [2,3]. J. A. Mundy et al (2017) demonstrated the existence of electronic inversion layers [2], whereupon it is proposed that the existence of polaronic states at head-to-head (H-H) domain walls (DWs) in erbium manganite, previously believed to be uncharged and therefore incapable of demonstrating DWC, in fact manifest in DWC above a certain applied threshold voltage. In addition to this, M. P. Campbell et al (2016), working on ytterbium manganite [3], have been able to successfully carry out Hall microscopy upon conducting tail-to-tail (T-T) DWs using an atomic force microscopy (AFM) tapping mode method, whereupon p-type carriers have been identified, and an upper bound estimate of carrier densities was formulated.

Our work builds upon both of these sizeable achievements. As reported in previous literature [2], erbium manganite is characterised by the existence of six fold DW vertices, whereby recent conjecture [3] proposes the aggregation of p-type carriers at T-T regions (the section of wall denoted AB in figure 1). Literature [2] also suggests that carriers with n-type character aggregate at the H-H regions (section denoted BC in figure 1). It follows that the junction ABC may demonstrate p-n diode characteristics.

Within the scope of this study we seek to present quantitative Hall measurements, which use a KPFM interleave technique whereupon surface potentials are mapped during the application of simultaneous orthogonal magnetic field and DW currents; this allows successful identification of carrier types and the calculation of carrier densities at naturally occurring DW p-n junctions. Early results indicate that a measurable Hall signal can be detected at T-T walls with a drive voltage of 10V, and thus the presence of p-type carriers has been confirmed. We also seek to corroborate the Hall data described above with four-probe resistivity measurements that examine the diode characteristics of the junction itself. With the aforementioned groundwork laid, we look for a proof-of-concept with which we can push forward towards the development of custom made p-n junctions and subsequently, p-n-p and n-p-n geometries. We believe that such advancements carry with them profound potential in regards to application, as well as for the development of our understanding of the fundamental physics at play.

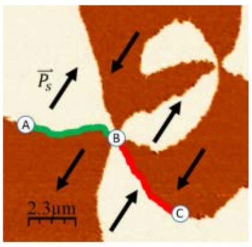

Fig 1. Lateral PFM scan depicting a six-fold vertex and theoretical p-n junction in in-plane polarized $ErMnO_3$

[1] J. Seidel et al (2009), Nature Materials, 8, 229 - 234
[2] J. A. Mundy (2017), Nature Materials, DOI: 10.1038/NMAT4878
[3] M. P. Campbell (2016), Nature Communications, DOI: 10.1038/ncomms13764

Revealing polarisation curling and flux closures in ferroelectric tunnel junctions using atomic resolution transmission electron microscopy (Invited)

J Peters, G Apachitei, R Beanland, M Alexe and A Sanchez

University of Warwick, United Kingdom

High-quality ultrathin ferroelectric films down to 3 unit cells (~1.2 nm) have been recently achieved [1], reinvigorating the interest of using oxides in non-volatile memory cells. Such a device is the ferroelectric tunnel junction (FTJ) that consists of a capacitor where the dielectric barrier is an ultrathin ferroelectric [2]. The thinness of the ferroelectric allows a current to tunnel across it which is modulated by the orientation of the ferroelectric's polarisation. To form a high-density device with multiple states, domain walls are required that are not energetically favourable. Instead, vortex-type structures are formed that are driven by depolarisation fields from bound charges in the ferroelectric.

Typically, vortex-like polarisation structures are studied in ferroelectrics between insulating layers where the bound charge cannot be screened and the depolarisation field is maximised. However, the lack of electrodes makes it hard to manipulate the polarisation for use in a device. It is then not so clear if the polarisation curling is induced from the absence of electrodes or if the screening from the free charge will compensate for the bound charges. The exact form of the polarisation is of interest as it may affect the device effectiveness or density.

Here we study working $Co/PbTiO_3/La_{0.7}Sr_{0.3}MnO_3$ (Co/PTO/LSMO) FTJ devices using aberration corrected scanning transmission electron microscopy (STEM). To fully reveal the polarisation in the layer the positions of all atoms is required, something that is not possible from conventional techniques. To achieve this, annular bright field (ABF) STEM imaging has been used with computer analysis to measure the positions of each atom. Calculating the relative displacements of each atom then give the polarisation on the unit cell level [3]. This reveals domain configurations in the FTJs ranging from Kittel type 180° domain wall to more complex Landau-Lifshitz flux-closures and vortex type domain configurations [4].

[1] Fong, D. D. et al. Ferroelectricity in Ultrathin Perovskite Films. Science 304, 1650–1653 (2004).
[2] Pantel, D., Goetze, S., Hesse, D. & Alexe, M. Reversible electrical switching of spin polarization in multiferroic tunnel junctions. Nat Mater 11, 289–293 (2012).
[3] Jia, C.-L. et al. Unit-cell scale mapping of ferroelectricity and tetragonality in epitaxial ultrathin ferroelectric films. Nat Mater 6, 64–69 (2007).
[4] Peters, J. J. P., Apachitei, G., Beanland, R., Alexe, M. & Sanchez, A. M. Polarization curling and flux closures in multiferroic tunnel junctions. Nat Commun 7, 13484 (2016).

Non-volatile ferroelectric domain wall memory

P Sharma[1], Q Zhang[1], D Sando[1], C Lei[2], Y Liu[3], J Li[4,5], V Nagarajan[1], J Seidel[1]

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Interfaces and boundaries between competing phases (ferroic domain walls, phase boundaries), and materials (for e.g. LaAlO3 and SrTiO3) have gathered immense interest as potential reconfigurable nanoelectronic elements. IBM is currently developing 'race-track memories' in which the high-density digital information is encoded in the form of magnetic domain walls, which can be injected and moved controllably along 3 dimensional (3D) ferromagnetic nanowires. Only recently, analogous research in ferroelectric materials has seen tremendous interest, because of much smaller domain wall sizes and the potential of electric field induced wall movement that could enable ultralow-power electronics.

Ferroelectric domain walls are atomically-sharp topological defects that separate regions of uniform polarization. The discovery of electrical conductivity in specific types of walls gave rise to "domain wall nanoelectronics", a technology in which the wall (rather than the domain) stores information. This paradigm shift critically hinges on precise nano-engineering of reconfigurable domain walls. Here, we demonstrate a prototype solid-state non-volatile ferroelectric domain wall memory, scalable to below 100 nm. The device can be read-out nondestructively at moderate voltages (~ 2V) exhibits relatively high OFF-ON ratios (~ 103) with excellent endurance and retention characteristics, and possesses multilevel data storage capacity. Our work thus constitutes an important step toward integrated nanoscale ferroelectric domain wall memory devices [1].

[1] P. Sharma, Q. Zhang, D. Sando, C.-H. Lei, Y.-Y. Liu, J.-Y. Li, V. Nagarajan, J. Seidel, Science Advances (2017) in press.

Non-collinear interfacial magnetism at a termination-controlled $SrRuO_3$ interface (Invited)

K Dörr[1], S Das[1], A Rata[1], I Maznichenko[1], A Ernst[2] and I Mertig[2]

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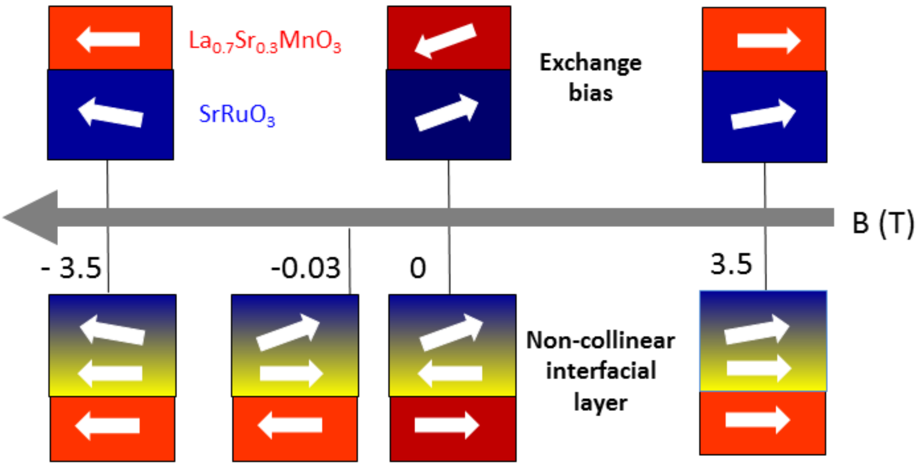
Strong interfacial magnetic coupling can create non-collinear spin arrangements. In an exchange spring magnet, the magnetization in a soft-magnetic component gradually rotates as a consequence of strong exchange coupling to a hard magnet. The Dzyaloshinskii-Moriya interaction caused by strong spin-orbit coupling in an adjacent layer (like Pt) is another source of non-collinear spin textures at interfaces and is responsible for the formation of chiral domain walls and Skyrmions. Interfaces of complex magnetic oxides are yet much less investigated in this respect than those in metals. Due to the intimate link between lattice and electronic degrees of freedom in transition metal oxides, novel types of chiral spin textures and alternative tools for tuning them can be expected. I will discuss two different interfacial magnetic structures which arise at termination-controlled interfaces between the itinerant ferromagnets SrRuO3 and $La_{0.7}Sr_{0.3}MnO_3$. A switchable interfacial layer with non-collinear spin texture has been detected in the hard-magnetic $SrRuO_3$ based on element-sensitive x-ray magnetic circular dichroism. Density functional theory indicates for this MnO_2-terminated interface a very large Mn-Ru indirect exchange interaction. In the case of a RuO_2-terminated interface, much weaker exchange coupling is consistent with the absence of such an interfacial layer. Switching the soft-magnetic $La_{0.7}Sr_{0.3}MnO_3$, the $SrRuO_3$ interfacial layer follows in rigidly coupled way, while the interface-far SrRuO3 remains unchanged, inducing a kind of horizontal domain wall in the interface-near SrRuO3. Our results go beyond the known exchange spring behavior and point to an interfacial mechanism altering magnetic anisotropy. They provide an example for interfacial control of non-collinear spin textures in complex perovskite-type oxides by atomic interface engineering.



Direct imaging of skyrmion internal structure and dynamic skyrmion processes (Invited)

D McGrouther, R Lamb, M Krajnak, S McVitie and R Stamps

University of Glasgow, United Kingdom

The Lorentz modes of transmission electron microscopy (TEM) provide an excellent tool for investigating the magnetic structure and dynamics of skyrmions in thin specimens possessing non-centrosymmetric crystal structures. For the study of skyrmion structure we have utilised our developed differential phase contrast (DPC) imaging mode [1,2], affording spatial resolution better than 3 nanometres. Applied to lattice skyrmions in FeGe at T=250K we observed the average skyrmion internal magnetic structure and measured the variation in skyrmion diameter as the applied field strength was varied. We also confirmed that lattice skyrmions possessed a degree of internal hexagonal symmetry and that there can exist a significant level of structural variation across the skyrmion lattice [3].

In related work we have used the Fresnel mode of TEM to observe dynamic processes involving skyrmions. By direct filming using a novel direct electron detector, Medipix3 [4], we have obtained movies of both induced and spontaneous skyrmion processes. In Cu_2OSeO_3 at T=20K we have studied the phase transition from the helical to skyrmion lattice state, induced by rapid increase of an applied magnetic field. A number of processes were observed, figure 1, which included helical reorientations, spontaneous single skyrmion formation and annihilation, prior to the skyrmion lattice phase finally establishing itself.

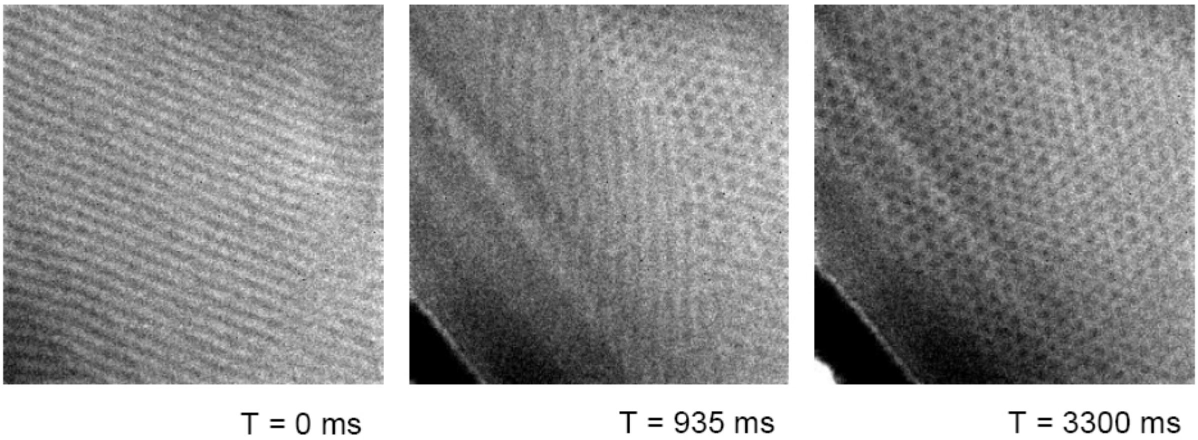


Figure 1. Fresnel images from a movie sequence of the phase transition from the helical to skyrmion state filmed at 100 frames per second.

[1] S. McVitie et al., Ultramicroscopy 152, 57 (2015)
[2] M. Krajnak et al., Ultramicroscopy 165, S. 42 (2016)
[3] D. McGrouther et al., New Journal of Physics 18, 095004 (2016)
[4] J. A. Mir et al., submitted to Ultramicroscopy, https://arxiv.org/abs/1608.07586 (2016)

Twist and turn - topological textures in ferromagnetic and ferroelectric nanostructures (Invited)

O Heinonen

Argonne National Laboratory, USA

“There’s plenty of room at the bottom” is how Richard Feynman’s famously introduced nanotechnology to the world. This statement is certainly true in the arenas of nanoscale ferromagnetic or ferroelectric structures. As the device dimensions shrink to below the scale of a micrometer, intrinsic length- and energy-scales can be made to compete. As a consequence, frustration can be designed into systems – on purpose or by accident – which can lead to interesting textures with novel static and dynamic behaviors. I will in this talk present a few different systems that I have studied together with a number of collaborators. A common theme is how patterning and/or interactions in nanoscale systems lead to topological textures. The first system is a magnetic thin film with out-of-plane anisotropy in contact with a heavy metal spin-orbit scatterer, such as Ta or Pt. This gives rise to an interfacial Dzyaloshinksii-Moriya interaction (DMI), and if a current is applied to the heavy metal, a spin Hall torque arises. By tailoring the current density to be non-uniform, magnetic skyrmion bubbles can be created in the thin film and pushed around[1,2]. However, skyrmion bubbles or lattices can also be created in centrosymmetric systems without DMI. A second system is the shape alloy Ni2MnGa. This material tends to have twins such that the anisotropy easy axis rotates 90 degrees between consecutive twins. In a thin film, the spacing between twins can be of the order of the thickness of the film. The competition between anisotropy, exchange, and magnetostatic energies can then give rise to a rich phase diagram, with a skyrmion lattice emerging at finite temperatures. Skyrmion or skyrmion-like textures are not confined only to ferromagnetic nanostructures. By patterning ferrolectric nanospheres[3] or nanodisks, interesting and topologically non-trivial ferroelectric polarization textures can emerge. Because of the electrostrictive coupling and, of course, the coupling to electrostatic fields, such ferroelectric systems can be controlled and manipulated with different external stimuli than magnetic ones. Finally, another class of systems are artificial spin ices, which are periodic arrays of single-domain magnetic island patterned from thin films. Artificial spin ices (ASIs) have interesting behaviors that stem from the competition and frustrated interactions. ASIs can also support topological defects, Dirac monopoles and Dirac strings. These defects have distinct dynamic signatures that can be probed experimentally. ASIs also support magnons, and because the magnetic order in the array can be reconfigured, ASIs can be viewed as reconfigurable magnonic lattices. While the magnon dispersion can be reconfigured, the magnon bands are typically topologically trivial. However, by introducing an interfacial DMI, for example by depositing the magnetic islands on a spin-orbit scatterer, topologically non-trivial magnon bands can emerge. Moreover, the bands can be set and re-set to be topologically trivial or non-trivial using, eg, an external magnetic field.
Support from the US Department of Energy, Office of Science, Materials Sciences and Engineering Division is gratefully acknowledged.

[1] Jiang et al, Science 349, 283 (2015).
[2] Phatak et al, Nano Letters 16, 4141 (2016)
[3] Mangeri et al, Nanoscale 9, 1616 (2017)

X-ray resonant magnetic diffraction as a tool for investigation of magnetic chirality (Invited)

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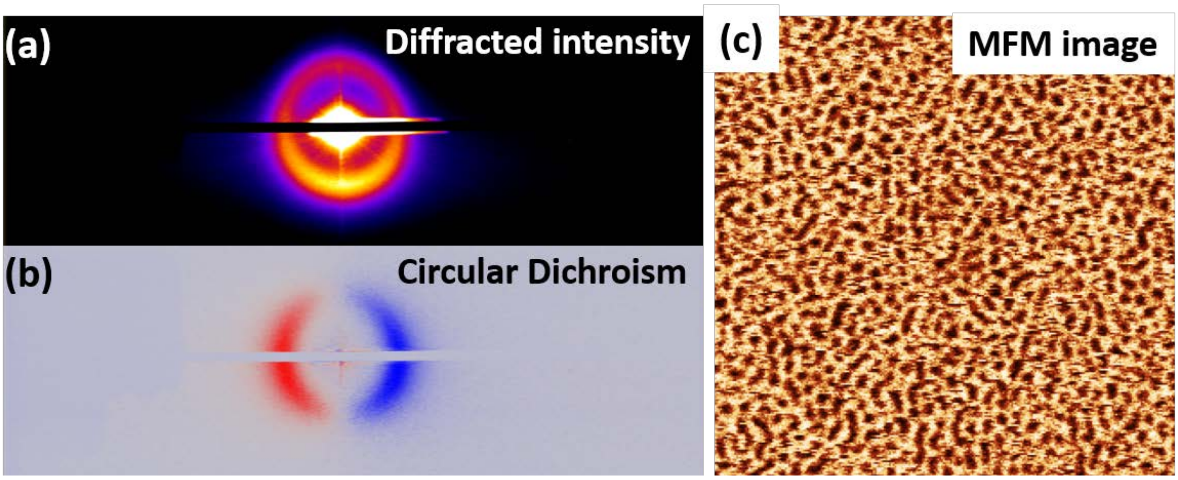
Nowadays, magnetic chirality has become a topic of utmost importance considering the ever-growing interest in static and dynamic properties of topological magnetic structures such as magnetic skyrmions and domain walls and their possible implications in future high-density data storage devices [1]. One effective way of inducing chiral magnetic structures is to consider magnetic systems showing a dominant Dzyaloshinskii-Moriya interaction (DMI) [2]. To master the stabilization of such magnetic objects one needs to access the magnetic chirality which remains a challenge. In the pioneer work of DÃ¼rr et al. [3], X-ray resonant magnetic diffraction (XRMS) has proven to be a powerful experimental approach to probe magnetic chirality. In this presentation, two magnetic systems will be discussed in the framework of XRMS: on one hand, Pt/Co multilayers in which DMI is a induced by the inversion symmetry breaking at the Pt/Co interfaces [4] and on the other hand, an investigation of BiFeO3 thin expitaxial layers. This latter is an archetypical antiferromagnetic-ferroelectric multiferroic [5], in which the â€œbulkâ€ DMI plays a major role in its magnetic configuration and in particular in the stabilization of the antiferromagnetic cycloid.



[1] A. Fert, V. Cros and J. Sampaio, Nature Nano. 8 152 (2013)
[2] I. Dzyaloshinskii, J. of Physics and Chemistry of Solids 4, 241 (1958), T. Moriya, Physical Review 120, 91 (1960).
[3] H.A. DÃ¼rr et al., Science 284 2166 (1999)
[4] A. Fert, Materials Science Forum 59, 439 (1990)
[5] G. Catalan and J.F. Scott, Adv.Mater. 21, 2463 (2009).

Topological spin textures in B20-type compounds with magnetic anisotropy engineering (Invited)

N Kanazawa

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Topological properties of skyrmions [1], such as topological Hall effect [2] and ultralow-current driven skyrmion motion [3], stimulate researches on design of new topological spin textures in pursuit of further novel functionalities. Examples of those spin structures include biskyrmions [4], Néel-type skyrmions [5,6], and chiral soliton lattice [7]. One guiding principle for creating such winding spin textures is utilizing antisymmetric spin exchange interaction, namely Dzyaloshinskii-Moriya (DM) interaction, allowed in crystals without local or global space inversion symmetry.

We have realized various chiral magnetic states in a prototypical skyrmionic material, so-called B20-type compounds, by changing DM interaction and magnetic anisotropy–which are controlled by spin-orbit interaction and device manufacturing. In this talk, we would like to present our recent results on chiral/topological magnetic structures and consequent unique transport properties in bulks and films of B20-type compounds [8,9].

This work is done in collaboration with Center for Emergent Matter Science (CEMS), Paul-Scherrer Institut (PSI), École polytechnique fédérale de Lausanne (EPFL), and Institut Laue-Langevin (ILL).

[1] N. Nagaosa and Y. Tokura, Nature Nanotech. 8, 899 (2013).
[2] A. Neubauer et al., Phys. Rev. Lett. 102, 186602 (2009).
[3] F. Joneitz et al., Science 330, 1648 (2010).
[4] X. Z. Yu et al., Nature Commun. 5, 3198 (2014).
[5] S. Heinze et al., Nature Phys. 7, 713 (2011).
[6] I. Kézsmárki et al., Nature Mater. 14, 1116 (2015).
[7] Y. Togawa et al., Phys. Rev. Lett. 108, 107202 (2012).
[8] N. Kanazawa et al., New J. Phys. 18, 045006 (2016).
[9] N. Kanazawa et al., Phys. Rev. B 94, 184432 (2016).
[10] N. Kanazawa et al., Nature Commun. 7, 11622 (2016).

Poster Session

Static and dynamic studies on the magnetic properties of Co1-xMnxFe2O4 nanoparticles

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[1]Moroccan Foundation for Advanced Science, Morocco, [2]Mohammed V-Agdal University, Morocco, [3]University Joseph Fourier, France

In this paper we report the evolution of magnetic properties of cobalt doped manganese nanoparticles in static and dynamic mode. The samples were prepared by Sol-gel method. The magnetic properties in static mode of the prepared samples indicate that the samples are ferrimagnetic materials. The Curie temperature and the saturation magnetization decreases with increasing Mn concentration in the $Co_{1-x}Mn_xFe_2O_4$ (x = 0; 0.5; 1) nanoparticles system. The variations of the blocking temperature (T_B) in this regime are also inversely proportional to Mn concentration. However in dynamic regime the variations of T_B are proportionally to the applied magnetic field frequencies. This kind of material can be used in the high frequency technology.

Skyrmion edge localized spin waves

M Mruczkiewicz[1], M Krawczyk[2], PGruszecki[3] and KGuslienko[3,4]

[1]Slovak Academy of Sciences, Slovakia, [2]Adam Mickiewicz University in Poznan, Poland, [3]Universidad del País Vasco, Spain, [4]The Basque Foundation for Science, Spain

An isolated magnetic skyrmion is known to possess a set of zero frequency excitations, that can acquire a finite frequency when symmetry is broken, also known as Goldstone modes. In addition, the high frequency spin waves perturbations over the fixed soliton background are present [1]. Here, with numerical simulations (mumax3) we are investigating the properties of the spin wave excitation over Neel-like magnetic skyrmion stabilized by the Dzyaloshinskii-Moriya interaction (DMI), see Fig 1 a). A discrete set of skyrmion edge localized modes is found, characterized by azimuthal index m, (see Fig 1 b). These modes can be identified as domain wall localized modes, so-called Winter's magnons [2,3]. Due to the presence of DMI and magnetization orientation (in-plane and perpendicular to spin wave propagation), non-reciprocal propagation is expected [4]. Large energy splitting between oppositely propagating spin waves is observed when DMI constant is varied. The influence of the nanodot shape on the coupling strength to unifiorm ferromagnetic resonance field is further investigated.

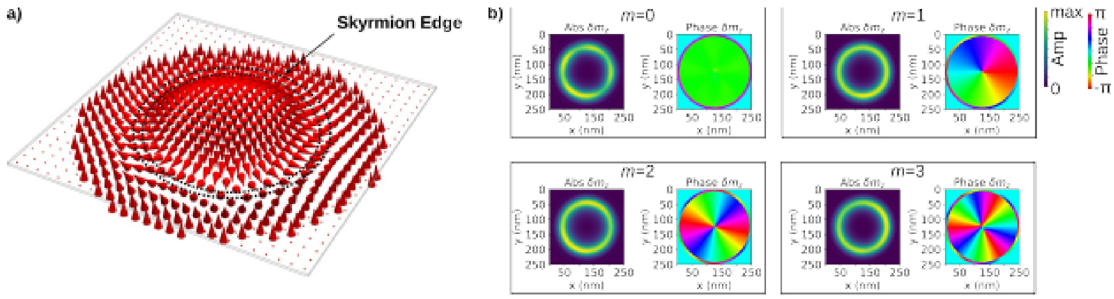

Figure 1. a) Magnetic skyrmion confined in a nanodot. b) Spatial distribution of the dynamic magnetization z-component for four spin wave modes localized at the skyrmion edge.

[1] M. Mruczkiewicz, M. Krawczyk, and K. Y. Guslienko, Physical Review B 95.9 (2017): 094414.
[2] J. M. Winter, Physical Review 124.2 (1961): 452.
[3] F. G. Aliev, et al., Physical Review B 84.14 (2011): 144406.
[4] M. Mruczkiewicz, and M. Krawczyk, Physical Review B 94.2 (2016): 024434.

Muon-spin relaxation signature of the skyrmion lattice phase

K Franke[1], B Huddart[1], M Worsdale[1], F Pratt[2], F Ziao[3], S Blundell[4], P Hatton[1], M Ciomaga Hatnean[5], A Štefančič[5], G Balakrishnan[5] and T Lancaster[1]

[1]Durham University, United Kingdom, [2]STFC RAL, United Kingdom,[3]Laboratory for Muon Spin Spectroscopy, Switzerland, [4]Oxford University, United Kingdom, [5]University of Warwick, United Kingdom

Skyrmions are topologically protected, nano-sized objects which have been shown to exist in the spin textures of a range of magnetic materials. Skyrmions arrange in a skyrmion lattice (SL) that is stabilised at a non-zero magnetic field and temperature in a small pocket of the phase diagram. As we have recently demonstrated in our muon-spin relaxation μ+SR work on these systems [1,2,3], μ+SR is a promising method for exploring the physics of the SL phase. Implanted muons in magnetically ordered materials precess in the internal magnetic field and act as very sensitive microscopic magnetometers. The spin relaxation yields information on the dynamics present in magnetic materials.

We have made μ+SR measurements on two skyrmion hosting materials: Co8Zn8Mn4 and GaV4S8. Co8Zn8Mn4 crystallises in the b-Mn-type structure. A SL phase is observed in the region 300 £ T £ 320 K in small applied field of around 10 mT. The skyrmion lattice forms in a plane perpendicular to the applied magnetic field and the skyrmions are of chiral Bloch-type where the spins rotate in the plane perpendicular to the radial direction[4]. In contrast GaV4S8 exhibits a non-chiral polar rhombohedral phase below 42 K. The SL phase is observed between T = 9 and T = 13 K in applied magnetic fields between B = 15 and 100 mT. This is an unusually broad temperature and field range for a SL. The orientation of the skyrmion texture aligns with the magnetic easy axis. These unique features appear to reflect the presence of a nonchiral Néel type skyrmion texture.

We have investigated the static and dynamic properties of these very different materials using

μ+SR and determine common signatures of the SL phase in the observed internal magnetic field and dynamics. The skyrmion phase is seen as a peak in the internal field (Figure1) and spin relaxation rate. We attribute the latter to dynamics associated with the skyrmion phase such as rotation and breathing modes of the SL occurring on the microsecond muon time scale.

[1] S. Zhang et al., Sci.Rep. 7, 123 (2017) [2] T. Lancaster et al., Phys. Rev B 93, 140412(R) (2016) [3] T. Lancaster et al., Phys. Rev B 91, 224408 (2015) [4] Y. Tokunaga et al. Nature Commun., 6 7638 (2015) [5] I. Kézsmárki et al., Nature Materials 14, 1116 (2015).

International Workshop on Topological Structures in Ferroic Materials

Transport properties and topological Hall effect measurements in B20 Fe1-xCoxGe epilayers

C Spencer[1], J Gayles[2,3], N Porter[1], F Freimuth[4], S Blügel[4], J Sinova[2,4,5], Y Mokrousov[4] and C Marrows[1]

[1]University of Leeds, United Kingdom, [2]Johannes Gutenberg Universität Mainz, Germany, [3]Texas A&M University, USA, [4]Peter Grünberg Institut and Institute for Advanced Simulation, Germany, [5]Institute of Physics ASCR, Czech Republic

Magnetic skyrmions can form in materials that possess a Dzyaloshinskii-Moriya interaction (DMI) [1,2]. In Mn1-xFexGe, the skyrmion size was found to diverge at a critical composition, corresponding to an inversion of the DMI chirality [3]. This sign change of the DMI has been reproduced with ab initio calculations [4].

We have used polarised neutron reflectometry (capable of revealing the helical structure in epitaxial FeGe films [5]) to find another divergence of the helical wavelength at x~0.6 in Fe1-xCoxGe epilayers, indicating an oscillating DMI strength as the Fermi level is scanned.

The theoretically calculated anomalous and topological Hall effect [4] (a possible marker of skyrmions) were found to have good agreement with recent experimental values from our FeGe films [6]. Figure 1 shows the measured anomalous Hall conductivity σAH at 5 K and the calculated DFT values. A good correlation can be seen for values up to x = 0.5 however the large values for σAH that are found theoretically for x = 0.6 and above are not seen experimentally perhaps due to disorder in real epilayers. Nevertheless, the convergence between theory and experiment shows that a complete description of the B20 germanide system within ab initio theories is within reach.

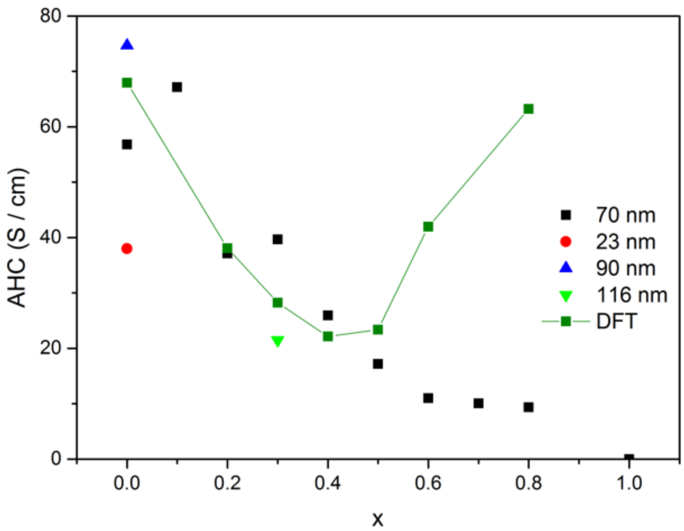

Figure 1 Anomalous Hall conductivity for $Fe_{1-x}Co_xGe$ epilayers at 5 K with x = 0 to 1 and DFT ab-initio calculations

[1] S. Mühlbauer et al., Science 323, 915-919 (2009).
[2] U.Roßler, A. Bogdanov, C. Pfleiderer, Nature 442, 797-801 (2006).
[3] K. Shibata et al., Nature Nano. 8,723–728 (2013)
[4] J. Gayles et al., Phys. Rev. Lett. 115, 036602 (2015)
[5] N. Porter et al., Phys. Rev. B 92, 144402 (2015)
[6] N. Porter et al., Phys. Rev. B 90, 024403 (2014)

Observation, compression, and electrical detection of single magnetic skyrmions in magnetic multilayer microdiscs

C Marrows[1], K Zeissler[1], M Mruczkiewicz[2], S Finizio[3], J Raabe[3], K Shahbazi[1], J Massey[1], P Shepley[1], MRosamond[1], T Moore[1] and G Burnell[1]

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Skyrmions are magnetic, knot like, quasiparticles that are of great interest not only for their potential in low current and high-density information storage but also for their emergent phenomena arising from their unique topological configuration. We have imaged room-temperature Néel skyrmion bubbles in perpendicularly magnetised polycrystalline multilayers patterned into 1 μm diameter dots using scanning X-ray transmission microscopy. The skyrmion bubbles can be nucleated by the application of an external magnetic field and are stable at zero field with a diameter of 260 nm. Applying an out of plane field that opposes the magnetisation of the skyrmion bubble core moment applies pressure to the bubble and gradually compresses it to a diameter of approximately 100 nm. On removing the field the skyrmion bubble returns to its original diameter via a hysteretic pathway where most of the expansion occurs in a single abrupt step. This contradicts analytical models of homogeneous materials in which the skyrmion compression and expansion are reversible. Micromagnetic simulations incorporating disorder can explain this behaviour using an effective thickness modulation between 10 nm grains.

When a charge carrier traverses though a magnetic material exhibiting a non-collinear magnetic domain structure its spin orientation adapts constantly, matching the magnetic moment configuration it experiences. This results in the electron acting as if it experienced an emergent magnetic field and hence the electron path changes and a Hall resistance can be measured. Here we show that we can not only detect a single skyrmion electrically, but that we also can separate the ordinary, the anomalous and the topological components of the Hall resistance to which it gives rise. This is achieved by using the unique combination of scanning transmission x-ray microscopy, a high resolution, non-disruptive, imaging technique, and low noise electrical transport measurements.

International Workshop on Topological Structures in Ferroic Materials

Spikes, stars and flowers: BaFe12-xO19: Ti4+, Co2+ observed by magnetic force microscopy

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Summary

Magnetic Force Microscopy (MFM) was used to image the basal plane of $BaFe_{12-2x}O_{19}$: Ti^{4+}, Co^{2+} where x ≈ 0, 0.2, 0.4 and 0.6. MFM images show broad, irregular domains with “star” “ring/star” and “flower” shaped features which can be attributed to the presence of Neél Spikes and Closure Domains. Increasing x led to more but smaller closure domains.

Introduction

$BaFe_{12}O_{19}$ is a hard ferrite with uses including magnetic storage and microwave circuitry. Figure 1A shows an MFM phase image of the basal plane of $BaFe_{12}O_{19}$. The image exhibits broad domains superimposed by three types of features: “stars”: spikes of high magnetic force; “ring/stars”: ring shaped features with star-like arms; and “flowers”: more complex, irregular features with spikes and troughs of high and low magnetic force respectively. Craik and Griffiths [1] describe the stars as being Neél spikes and the larger features as being closure domains due to inclusions in the material.

Experiment and Results

$BaFe_{12}O_{19}$ single crystals of various thicknesses doped with Ti^{4+} and Co^{2+} were synthesised using the top seeded method by combining $BaCO_3$, Fe_2O_3, TiO_2 and CoO in a BaO/B_2O_3 flux. Magnetic Force Microscopy phase images were made using a Park NX10 atomic force microscope and Park MFMR cantilevers. Samples were measured over a 50x50µm area.

Figures 1 A-D show MFM phase images measured for $BaFe_{12-2x}O_{19}$ where x ≈ 0, 0.2, 0.4 and 0.6. All three images show “star”, “ring-star” and “flower” type features and as x increases, the number of these features also increases suggesting that the number of inclusions logically increases as the number of impurities does. However the average diameter of the “ring-star” type features decreases as x increases.

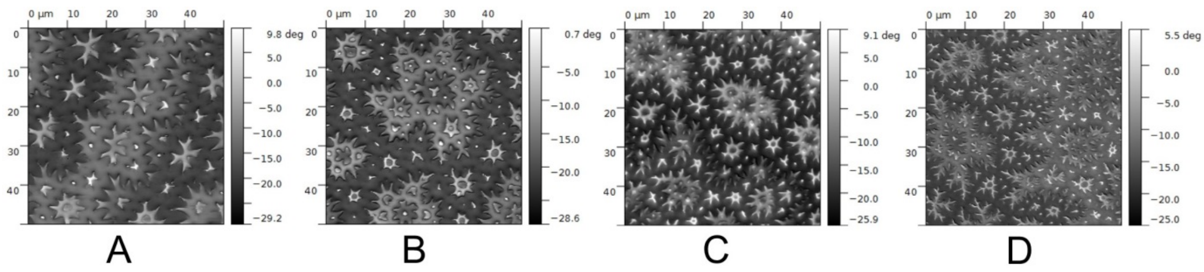

Figure 1. MFM phase images of the basal plane of $BaFe_{12-2x}O_{19}$ where x ≈ : A: 0, B: 0.2, C: 0.4, D: 0.6

[1] Craik D.J., Griffiths P.M., Proc. Phys. Soc., 73, 1 (1959)

Investigation of changing velocity asymmetry and DMI in chiral domain walls of Pt/Co/Ir/Ta multilayers

K Shahbazi[1], J Kim[2], V Jeudy[2], T Moore[1] and C Marrows[1]

[1]University of Leeds, United Kingdom, [2]Univerites Pris-Sud, France

Designing multilayer stacks with both high Dzyaloshinskii-Moriya interaction (DMI) and spin Hall effect (SHE) is of great current interest for spintronic devices exploiting chiral domain walls (DW) or skyrmions. The idea here is to sandwich a ferromagnetic layer within two other layers having large and opposite DMI/SHE. Pt/Co/β-Ta trilayers have proved to be promising to get high SHE [1]. However, Pt has a high DMI [2], which is low for β-Ta [3]. Alternatively, Ir has a large opposite DMI [3] but an unknown SHE. Here we study the insertion of Ir at the Pt/Ta interface of such a trilayer, and measure the DMI by the bubble expansion method, where an in-plane field H_{inP} interacts with the DMI to break the symmetry of left- and right-moving chiral DWs [4, 5]. Figure 1 shows our data. Whilst we have confirmed that all the data are in the creep regime, but there is nevertheless an unexpected restoration of the velocity symmetry for large in-plane fields. Our results join other recent reports of anomalies found when applying this method in the creep regime [6, 7], suggesting that more sophisticated models than those initially proposed by Je et al. [5] are needed. As a result, we are proposing a model based on DW's elastic energy redefining the dependence of DW (elastic)energy on in-plane field which can describe some aspects attributed to change of velocity asymmetry of chiral DWs.

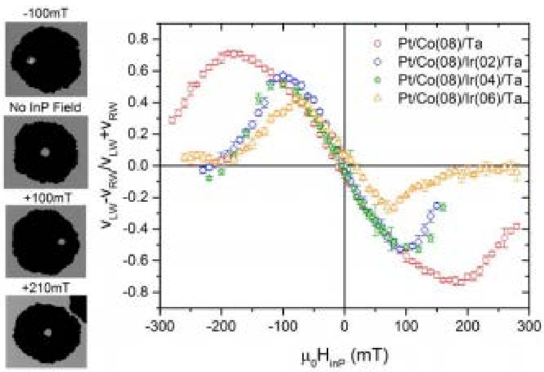

Figure 1. Images of bubble expansion in presence of in-plane field with different strength, showing that propagation gets symmetrical again in high in-plane fields (right). Velocity asymmetry with respect to applied in-plane field for samples with different Ir thickness (left). Calculated velocity differences are for DWs on the left and right of the bubble, each point is average of 3 images.

[1] S. Woo, et al., Applied Physics Letters, 105 (2014).
[2] SampaioJ, et al., Nat Nano, 8, (2013) 839-844.
[3] J. Torrejon, et al., Nat Commun, 5 (2014).
[4] A. Hrabec, et al., Physical Review B, 90, (2014) 020402.
[5] S. G. Je, et al., Physical Review B, 88, (2013) 214401.
[6] R. Lavrijsen, et al., Physical Review B, 91, (2015) 104414.
[7] M. Vanatka, et al., arXiv preprint arXiv:1504.00933 (2015).

Quantitative multi-scale x-ray imaging of embedded defects and interfaces in ferroic oxides

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Technical University of Denmark, Denmark

The distortions created by domain walls, dislocations and substrate-film interfaces can profoundly affect both local and global functionality. Understanding how and over what range they occur necessitates mapping strain at the sub-micron scale without spurious effects from the sample geometry – a critical and outstanding challenge. Now, dark-field x-ray microscopy promises a new way to quantitatively map nano-scale defect structures and their distortion fields within millimeter-sized samples. Spatial and angular resolution is ~70 nanometers and ~0.001°, respectively, while measurements are sufficiently fast that domain reconfiguration can be captured *in situ* in real time. The technique has been tested on number of prototypical phenomena in ferroic systems to date: natural domain structures around embedded grain boundaries in $BaTiO_3$ ceramics, domain reconfiguration during phase transformations in $KNbO_3$ single crystals, and low-density dislocation networks in epitaxial films of $BiFeO_3$. Despite their inherent differences, these examples all contained highly heterogeneous strain fields over distances of several microns – in contrast with theoretical predictions. This subtle but widespread symmetry breaking has the potential to explain many phenomena observed in macroscopic samples and devices that are not expected in thin cross-sections or unconstrained continuums. Furthermore, this new ability to directly characterize complex topological phenomena *in-situ* is a key step towards formulating and validating multi-scale models that account for the entire heterogeneity of the material.

Calibrated magnetic force microscopy with domain wall probes

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Magnetic force microscopy (MFM) qualitatively resolves changes in magnetisation, but has limited quantitative capabilities and difficulties measuring heterogeneous samples. Here, a custom-made domain wall probe (DWP) with a *V*-shaped nanostructure is fabricated and trialled against commercial low moment and standard moment probes (LMP and SMP, respectively). The probe stray field profiles are then quantified for calibrated magnetic measurement. A domain wall (DW) is localised near the physical apex of the DWP. As confirmed by electron holography, a localised stray field emanates from the probe apex, giving it similar resolution and sensitivity to the LMP but with higher coercivity and stability, preventing switching artefacts.

The stray fields of the three probes are calculated using the tip-transfer function (TTF) [1] and quantitatively compared. This was determined by imaging a thin reference film (Co/Pt), which has large perpendicular anisotropy and well-defined magnetic properties. The TTF is further qualified for calibration by applying it to predict the MFM response of an *L*-shaped permalloy nanostructure by convolving TTF results with a surface charge map calculated from micromagnetic modelling [2]. The simulated phase maps were compared with experimental results and demonstrate a good match for the LMP and DWP; however, failed to consider the effect of strong stray fields on the sample in the case of SMP. In terms of simulations, this can be resolved with a more rigorous model but in practice the present work perfectly demonstrates the need for probes that can image both soft and hard magnetic samples without sample perturbation and probe switching, respectively. When considering these attributes, the DWP surpassed the commercial counterparts in this study.

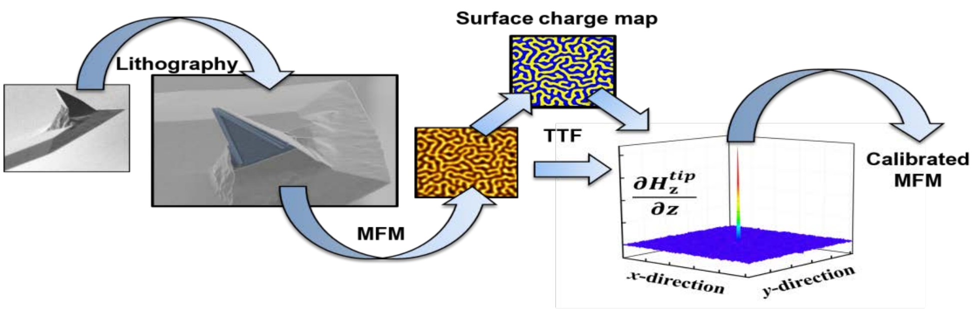

Fig 1. (From left to right) SEM image of commercial MFM probe and the DWP after lithographically etching the V-shaped nanostructure. From MFM measurements of the reference film (brown/gold) and the material magnetic properties the surface charge map (blue/yellow) is calculated. The stray field of the probe is calculated in Fourier space by deconvolving both images with a Wiener invert filter.

[1] S. Vock, C. Hengst, M. Wolf, K. Tschulik, M. Uhlemann, Z. Sasvári, D. Makarov, O. G. Schmidt, L. Schultz, and V. Neu, “Magnetic vortex observation in FeCo nanowires by quantitative magnetic force microscopy,” Appl. Phys. Lett., vol. 105, no. 17, p. 172409, Oct. 2014.

[2] A. Manzin, V. Nabaei, H. Corte-Leon, O. Kazakova, P. Krzysteczko, and H. W. Schumacher, “Modeling of Anisotropic Magnetoresistance Properties of Permalloy Nanostructures,” IEEE Trans. Magn., vol. 50, no. 4, pp. 1–4, Apr. 2014.

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