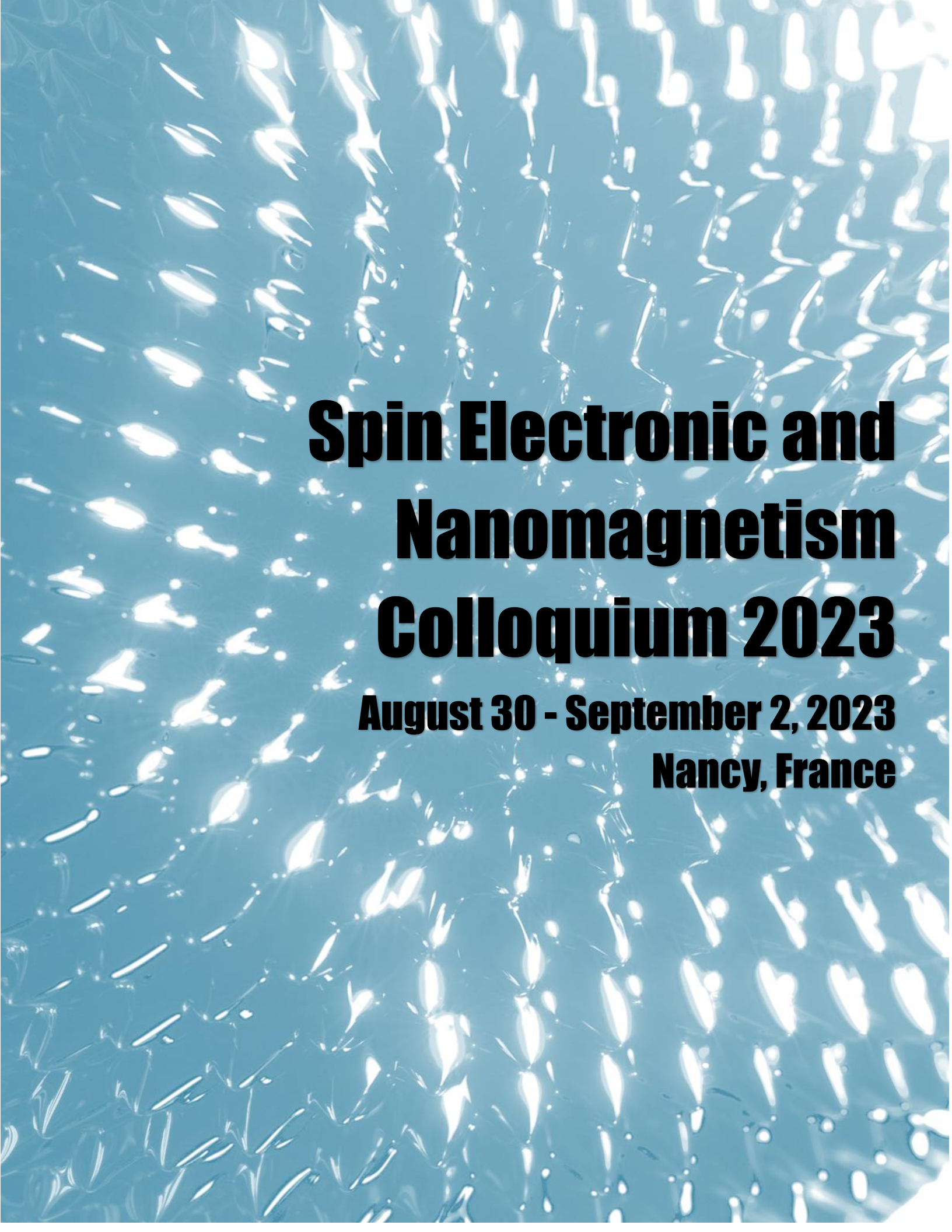

Spin Electronic and Nanomagnetism Colloquium 2023

August 30 - September 2, 2023

Nancy, France

Date: Wednesday 30th August 2023 - Saturday 2nd September 2023
Location: Nancy (France), C.C.I. MEURTHE ET MOSELLE Chambre de Commerce et d'Industrie*

* : 53 rue Stanislas, Nancy

INTRODUCTION

Spintronics, or spin electronics, exploits an additional property of the electron, namely its quantum property of spin. It offers new possibilities for applications such as highly sensitive sensors, high-density data storage and energy-efficient memories, computing, and telecommunications. Moreover, new fundamental topics are emerging, such as topological spin structures, topological insulators, Majorana fermions, antiferromagnetic spintronics, spin photonics, spin-orbitronics, spin optics, ultra-fast phenomena, out-of-equilibrium magnetism, THz emission, and spin-caloric phenomena. These advances make use of the fascinating developments of new materials controlled at the atomic scale and characterization techniques that allow us to probe those materials at ultimate scales, including length, time, temperature, and field.

The purpose of the Spin Electronics and Nanomagnetism colloquium is to bring together international experts from different communities, including fundamental physics (experimental and theoretical) and materials science, to provide a broad overview of the state-of-the-art and perspectives. Additionally, it will provide an opportunity to celebrate the birthday of Professor Eric E. Fullerton and his important contributions to the field of Spin Electronics and Nanomagnetism.

Organization committee

Dr. Andreas BERGER (CIC nanoGUNE – Spain)
Prof. Andrew KENT (Director, Center for Quantum Phenomena - New York University USA)
Dr Dafiné RAVELOSONA (Co-Founder/CTO Spin-Ion Technologies, Centre de Nanosciences et de Nanotechnologie (C2N) – France)
Prof. Axel HOFFMANN (Materials Science and Engineering at the Grainger College of Engineering, University of Illinois – USA)
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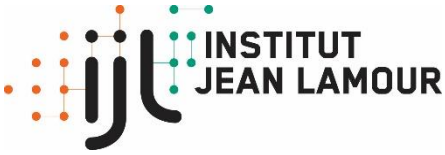
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Spin Electronic and Nanomagnetism Colloquium 2023

PROGRAM

Wednesday August 30th	Thursday August 31st	Friday Sept 1st	Saturday Sept 2nd
	9:00-9:25 George De Coster	9:00-9:25 Shirley Meng	9:00-9:25 Kai Liu
	9:25 - 9:50 Biswa Sahoo	9:25 - 9:50 Sergio Montoya	9:25 - 9:50 Bernard Dieny
9:30 - 10:00 Welcome & Coffee	9:50 - 10:15 David Lederman	9:50 - 10:15 Shaya Fainman	9:50 - 10:15 Victoire de Margerie
10:00 - 10:25 Ivan Schuller	Coffee Break - 15 Min.	Coffee Break - 15 Min.	Coffee Break - 15 Min.
10:25 - 10:50 Chris Leighton	10:30 - 10:55 Edwin Fohtung	10:30 - 10:55 Michael Flatte	10:30 - 10:55 Johan Akerman
10:50 - 11:15 Mike Coey	10:55 - 11:20 Peter Fischer	10:55 - 11:20 Axel Hoffmann	10:55 - 11:20 Kristiaan Temst
11:15 - 11:40 Theo Rasing	11:20 - 11:45 Aletta Prinsloo	11:20 - 11:45 Andrey Kiryliuk	11:20 - 11:45 Ray Osborn
11:40 - 12:05 Jim Rhyne	11:45 - 12:10 Sujoy Roy		11:45 - 12:10 Dafiné Ravélosona
Lunch / Posters	Lunch / Posters		Lunch / Posters
2:00 - 2:25 Hans Nembach	2:00 - 2:25 Herman Durr	***Meeting on Stanislas Square - Social event (Guided Walking Tour / City Train)***	2:00 - 2:25 Bert Koopmans
2:25 - 2:50 Dustin Gilbert	2:25 - 2:50 Roopali Kukreja		2:25 - 2:50 Casey Miller
2:50 - 3:15 Roy Chantrell	2:50- 3:15 Matt Gilbert		2:50- 3:15 Andreas Berger
3:15 - 3:40 Vitaliy Lomakin	3:15 - 3:40 Tom Thomson		3:15-3:40 Stephane Mangin
Coffee Break - 20 Min.	Coffee Break - 20 Min.		
4:00 - 4:25 Julius Hohlfeld	4:00 - 4:25 Jeff Brock		
4:25 - 4:50 Rudolf Schaefer	4:25 - 4:50 Romain Lebrun		
4:50 - 5:15 Andrew Kent	Posters		
Posters			
		6: 30 - Bus (Place de la république - Next to train station)	
7:00 PM Wine & cheese (musée des Beaux-Arts) - 3 x Visits	***7:00 PM Welcome Cocktails (Hotel de Ville) - Poster Prize***	***7:00 PM Gala Diner - Chateau d'Art sur Meurthe***	

Wednesday August 30th

9:30 – 10:00
Welcome & Coffee
10:00 – 10:25
From Metallic Superlattices to Neuromorphic Computing
Ivan Schuller
10:25 – 10:50
Origin of the ultrahigh conductivity in the delafossite metal PdCoO2
Chris Leighton
10:50 – 11:15
Some aspects of amorphous transition-metal alloys revisited
Mike Coey
11:15 - 11:40
Optical control of Magnetism: from ultrafast switching to brain inspired computing
Theo Rasing
11:40 – 12:05
Magnetic Coupling in Ferrite Nanoparticles Revealed by Polarized SANS and Inelastic Neutron Scattering
Jim Rhyne
12:05 AM - 2:00 PM: lunch & posters
2:00 - 2:25
Determination of the saturation magnetization and Heisenberg Exchange from spin-wave dispersion measurements
Hans Nembach
2:25 - 2:50
Using neutrons to probe skyrmions in Gd/Fe thinfilms
Dustin Gilbert
2:50 - 3:15
The evolution of models of FePt
Roy Chantrell
3:15 - 3:40
Multi-physics micromagnetic models and solvers
Vitaliy Lomakin
Coffee break: 20 minutes
4:00-4:25
Different ways to control all-optical switching in Gd-based ferrimagnets
Julius Hohlfeld
4:25 – 4:50
Magneto-optics, revisited
Rudolf Schaefer
4:50 - 5:15

A friendship and collaboration that started with Co/Ni
Andrew Kent

Origin of the Ultrahigh Conductivity of Metallic Delafossites

Y. Zhang[1], F. Tutt[1], G. Evans[2], W. Seyfried[2], P. Sharma[1,3], G. Haugstad[4], B. Kaiser[1], J. Ramberger[1], S. Bayliff[3], Y. Tao[1], M. Manno[1], J. Garcia-Barriocanal[4], R. Fernandes[3], T. Birol[1], and C. Leighton[1]

[1]Chemical Engineering and Materials Science, University of Minnesota, USA
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The delafossites are a class of complex oxides with general chemical formula ABO_2 that have been available in synthetic form since the early 1970s [1]. Some of these delafossites are metallic, where conductive triangular sheets of A^{1+} ions are interspersed with insulating $B^{3+}O_6$ edge-sharing octahedral layers, generating a remarkably simple electronic structure at the Fermi level [1,2]. Only in the last 20 years, however, was it understood that despite their highly anisotropic (essentially 2D) complex-oxidic nature, metallic delafossites (particularly $PdCoO_2$ and $PtCoO_2$) are the *most conductive oxides known*, for reasons that remain poorly understood [1]. In particular, their room-temperature resistivity is better than Au and their low-temperature resistivity falls as low as 8 nΩ cm, generating mean-free-paths of ~20 μm [1]. These extraordinary values have led to a slew of recent advances in condensed matter and materials physics [*e.g.*, 1-6]. To reach such low-temperature values, it is widely accepted that these materials must somehow be ultrapure and ultraperfect, although the methods for their growth (which produce only small crystals) are not typically capable of such [1].

In this presentation, we first report a new approach to $PdCoO_2$ bulk crystal growth, using chemical vapor transport to achieve order-of-magnitude gains in size and mass, the highest structural qualities yet reported, and record residual resistivity ratios ($440 < RRR < 760$). Nevertheless, the first detailed mass spectrometry study of these materials reveals that they are definitively *not* ultrapure, typically harboring 100s-of-part-per-million impurity levels. Through a detailed analysis however, we demonstrate that the fundamental crystal chemistry of delafossites dictates that very few of these impurities can feasibly substitute for Pd on the A site, whereas many can easily substitute for Co on the B site. The conductive Pd sheets are thus ultrapure while the Co-O octahedral layers getter the vast majority of the impurities. The total impurity density on the Pd sheets is deduced to be ~1 ppm, which we show to be quantitatively consistent with the observed residual resistivity *via* unitary-scattering-limit calculations [7]. We thus conclude that "sublattice purification" is a central mechanism in the metallic delafossites, significantly demystifying their ultrahigh low-temperature conductivity and mean-free-path [8]. Many exciting opportunities are opened up, including the possibility of long-range spin transport.

Work supported primarily by the US Department of Energy through the University of Minnesota Center for Quantum Materials under DE-SC0016371.

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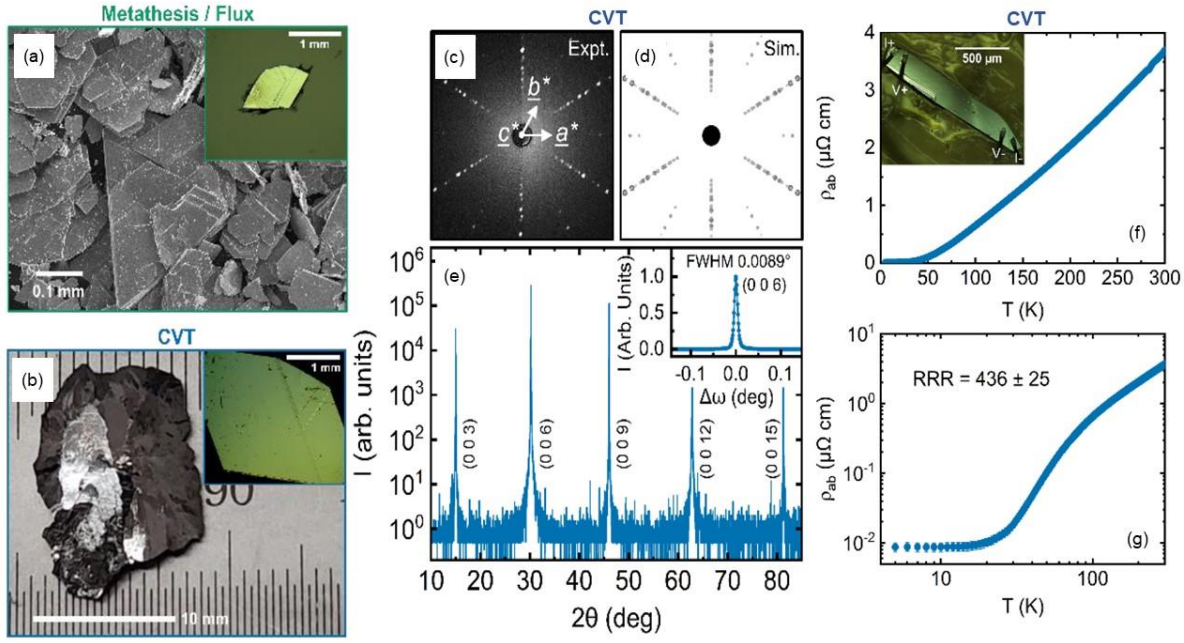

Figure 1: (a,b) Comparison of standard metathesis/flux-grown $PdCoO_2$ crystals and new CVT-grown crystals. (c-e) Laue and high-resolution single-crystal X-ray diffraction characterization of CVT-grown $PdCoO_2$. The rocking curve width is a record for metallic delafossites. (d,e,) *a-b* plane resistivity of CVT-grown $PdCoO_2$, showing record RRR.

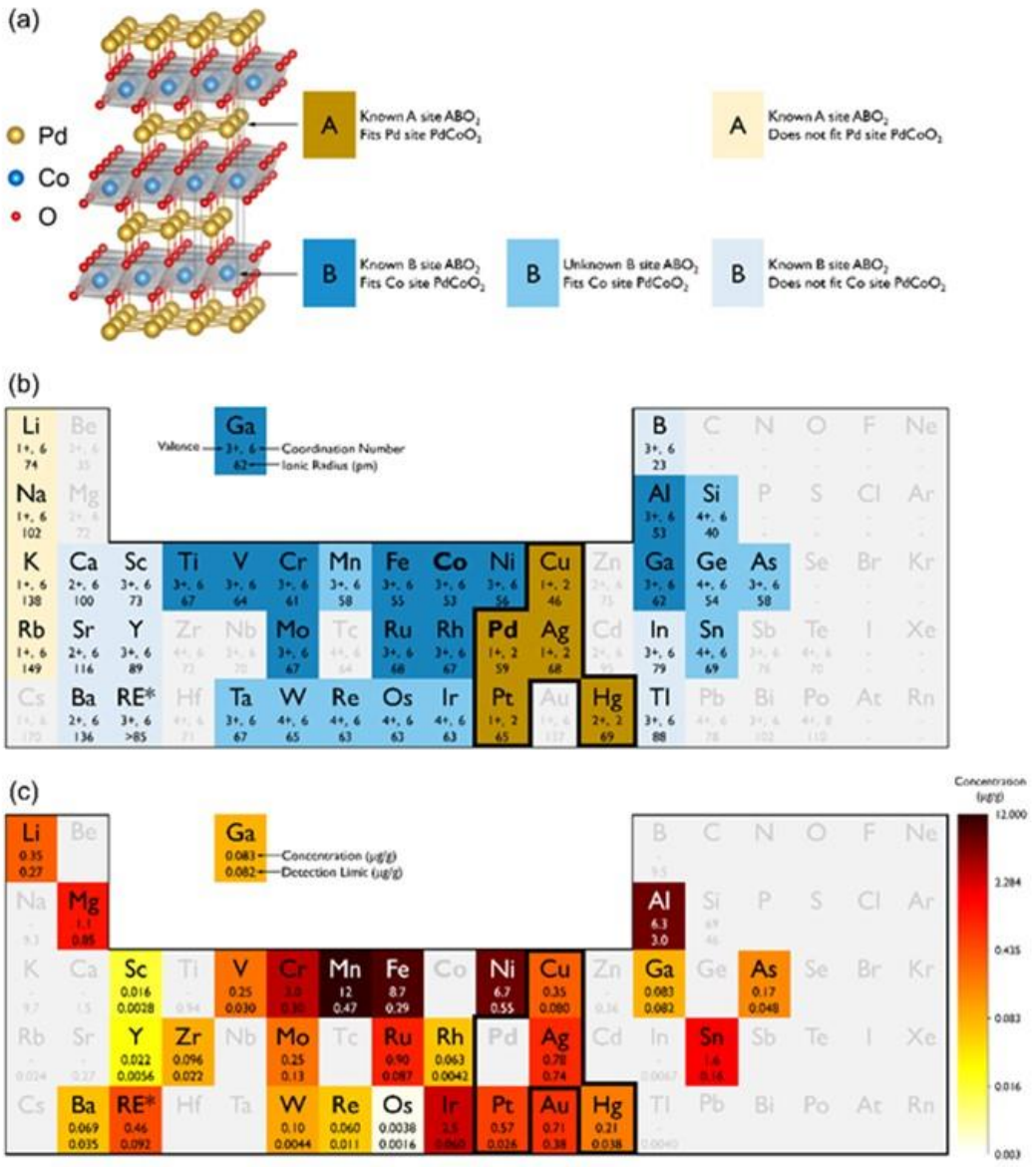

Figure 2: (a) Crystal structure of $PdCoO_2$ and classification scheme for potential A-site and B-site substitutional impurities. (b) Periodic table of potential A-site and B-site substitutional impurities. Note the only four elements that can feasibly substitute for Pd (bold border). (c) Concentrations of impurities in CVT-grown $PdCoO_2$ (the scale to the right is in weight-basis ppm). Note the sub-ppm concentrations of the only four elements that can feasibly substitute for Pd (bold border).

Some Aspects of Amorphous Rare-Earth Transition-Metal Alloys Revisited

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School of Physics and CRANN, Trinity College Dublin, Ireland

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Intermetallic compounds of 4*f* and 3*d* elements, especially Fe and Co were intensively investigated in the last four decades of the 20th century, and the roles of crystal structure, exchange and crystal field were elucidated. Important consequences were rational design permanent magnets with strong uniaxial anisotropy using an appropriate light rare earth ($SmCo_5$, $Nd_2Fe_{14}B$), uniaxial ferrimagnets with compensation ($TbCo_3$) and cubic ferrimagnets with strong magnetostriction but no net anisotropy ($Tb_{0.3}Dy_{0.7}$)Fe_2. The nonmagnetic rare earth yttrium was invaluable for isolating the 3*d* contribution to the magnetism. When high-quality metallic thin films began to be produced by sputtering 1970s, it was found that some 4*f*-3*d* binaries could be deposited as amorphous films which exhibited perpendicular magnetic anisotropy. Ferrimagnetic Gd-Fe-Co magneto-optic recording media with compensation point writing were an important development [1]. Amorphous alloys with strongly anisotropic rare earth elements tend to have magnetic ground-states where the rare earth moments freeze along randomly-oriented axes, with a net magnetic moment — parallel or antiparallel to that of Fe or Co [2].

A revival of interest in these materials has been spurred by several developments. One is the reappraisal of transverse magnetotransport (anomalous, spin and orbital Hall effects) in terms of real- or reciprocal-space Berry curvature. Atomic-scale simulations of atomic and magnetic structures and excitations have improved vastly in the past 50 years. The observation in 2013 of ultra-fast single-pulse all-optical toggle switching in thin films of perpendicular ferrimagnetic amorphous $Gd_x(FeCo)_{1-x}$ with $x \approx 0.25$ [3] opened new perspectives for magneto-optic applications, and understanding of the transient collapse of magnetization and anisotropy [4]. A new study of spin and orbital magnetism and magnetotransport in amorphous $Y_{1-x}Co_x$ will be presented, which allows a reassessment of the noncollinear magnetic structures of amorphous alloys with a heavy rare earth, Th, Dy or Er., and its temperature dependence. Densities and atomic coordination are compared with those of a relaxed model of random dense packing of two types of spheres with a volume ratio of 3:1, which gives a packing fraction of 0.633 ± 0.004 regardless of the value of *x*. A notable feature is the large orbital moment of 0.31 μ_B of Co in a-YCo_5 deduced by XMCD, which is attributed to the low density.

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All optical control of magnetism for energy efficient and brain inspired computing

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The ability to switch magnets between two stable bit states is the main principle of digital data storage technologies since the early days of the computer. Since our demonstration of magnetization reversal by a single 40 femtosecond laser pulse, the manipulation of spins by ultra-short laser pulses has developed into an alternative and energy efficient approach to magnetic recording [1]. Plasmonic antennas have allowed to push this All-optical switching (AOS) even down to nanometer length scales [2], while photonic networks in principle allow the development of an optically switchable MRAM [3].
While for a long time, AOS was exclusively observed in ferrimagnetic alloys, the work of Mangin and Fullerton demonstrated AOS in a broad range of ferromagnetic multilayer materials [4], albeit that in those examples a large number of pulses were required. By studying the dynamics of this switching process, we have, jointly with Fullerton's group, discovered that this switching is a 2-step process [5], involving nucleation and domain wall motion. This recently led us to the subsequent demonstration that highly efficient AOS can be achieved by using pairs of femto/pico-second laser pulses [6].
However, new ICT technologies, such as Artificial Intelligence lead to a compute demand that faces a doubling every 2-3 months [7], outpacing Moore's law for computer hardware and leading to a dramatic increase of the energy cost of computing, while already today computing systems consume about 7% of the global electrical energy production [8,9]. Therefore, development of radically new physical principles that combine energy-efficiency with high speeds and high densities is crucial for a sustainable future.
One of those new principles is neuromorphic computing, that is inspired by the notion that our brain uses a million times less energy than a supercomputer while, at least for some tasks, it even outperforms the latter. Ultimately, future brain-inspired technologies should provide room temperature operation down to picosecond timescales, nanoscale dimensions and at an energy dissipation as low as the Landauer limit (~zJ).

In this talk, I will discuss the state of the art in ultrafast manipulation of magnetic bits and present some first results [10] to implement brain-inspired (and Fullerton-inspired) computing concepts in magnetic materials that operate close to these ultimate limits.

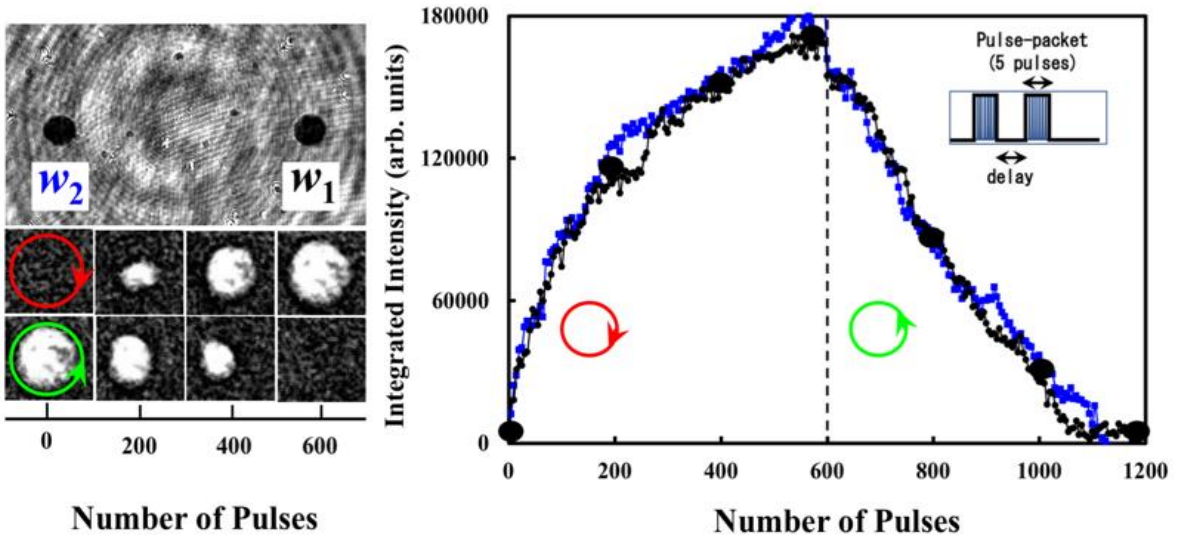

Fig. 1. (Left): Magneto-optical image of two physically-separated laser-written synaptic weights, w_1, w_2 (dark spots); the bottom shows eight background subtracted images illustrating evolution of the magnetization changes due to the right (top row) and left (bottom row) circularly-polarized fs laser pulses irradiating the Co/Pt sample. (Right): Extracted intensity changes as function of the number of laser pulses, demonstrating continuously-controllable weights, shown in black (blue) for w_1 (w_2). Black solid disks correspond to the images in the bottom rows of (a). The inset shows the pulse packets used for learning.

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MAGNETIC COUPLING IN FERRITE NANOPARTICLES REVEALED FROM POLARIZED SANS AND INELASTIC NEUTRON SCATTERING

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This talk will review the technique of polarized neutron small angle scattering and its application to the magnetic structure of spinel nanoparticles, specifically Fe ferrite (magnetite) [1] and Co ferrite [2].
The nanoparticles were prepared by a surfactant method [3] and then washed to remove all but a thin capping layer of oleic acid producing powder-like samples with minimum agglomeration. Transmission electron microscopy (TEM) data on the magnetite nanoparticles revealed a narrow (0.2 nm) distribution of particle sizes about a mean particle diameter of 9.0 nm. The nanoparticles self-assemble into face-centered cubic (FCC) crystalline nanoparticle arrays of lattice parameter 13.6 nm with a coherence of about a micron. The existence of this crystalline array is confirmed from small-angle neutron scattering (SANS) measurements that yielded a Bragg peak at Q = 0.080 A^{-1} arising from the dominant (111) reflection of the FCC array.
The inclusion of incident neutron polarization and post-scattering polarization analysis to the SANS data (PASANS) provides four scattering cross sections, two of them reflect scattering for which the incident neutron spin is preserved in direction (non-spin-flip cross sections) and two for which the spin direction is inverted during the scattering process (spin-flip cross sections). Data were taken both in a remnant (0.005 T) applied magnetic field as well as in a 1.2 T saturating field and at temperatures between 300K and 10K [1,2]. Analysis of the four scattering cross sections for data taken in a 1.2T field at 200K on magnetite nanoparticles revealed that the particles consist of a core-shell structure exhibiting an ≈ 7.4 nm diameter core having ferrimagnetic spin alignment (similar to bulk magnetite) surrounded by a 0.8 - 1.2 nm thick shell in which the spins are canted ferrimagnetically away from the direction of the applied field and the core spins. The shell thickness and the effective spin canting angle vary with temperature in the range 160K – 300K. The core-shell structure does not form in zero applied field or when cooled to low temperature in zero applied field demonstrating that the shell is of magnetic and not chemical origin. The surface layer canting angle is determined by a competition of exchange, dipolar, anisotropy, and Zeeman energies [4].
In contrast to the core/shell magnetic structure of magnetite nanoparticles, similarly sized nanoparticles of Co ferrite, which exhibit a higher ratio of anisotropy to exchange interaction, show an average net canting angle of all spins in a nanoparticle with respect to the applied field [2].

In an effort to explore the dynamics of these unusual magnetic states, inelastic scattering measurements of spin wave energies versus wave vector transfer have been made on a related system consisting of magnetite core|manganese ferrite shell nanoparticles [5]. These results revealed a quadratic dispersion of the spin excitations with a spin stiffness parameter D = 51 meV-A^2 significantly reduced from bulk ferrites. Remarkably these data demonstrate that the spin waves originate from dipolar coupling *between* nanoparticles and not from exchange coupling *within* individual nanoparticles.

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Simultaneous determination of the Heisenberg exchange, thickness and saturation magnetization from the spin-wave dispersion

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The Heisenberg exchange A_{ex} is a critical materials property for ferromagnetic order. Its experimental quantification remains a challenge for ultrathin magnetic films, which are common in today's memory and logic devices. There exist many different measurement approaches to determine the exchange parameter, which all have their respective challenges. These approaches include neutron scattering [1], determination of the Curie temperature, measurement of perpendicular standing spin-wave modes (PSSWs) with ferromagnetic resonance (FMR) or Brillouin Light Scattering spectroscopy (BLS) [2], spin-torque FMR measurements of localized spin-wave modes on full devices [3] or application of Bloch's $T^{3/2}$-law to temperature dependent magnetometry data [4]. All of these approaches have their respective unique challenges. For example, polarized Neutron scattering has a very small scattering cross-section, which makes it impossible to use for technological relevant ultrathin magnet films. The analysis of PSSWs requires careful consideration of the pinning of the PSSWs at the boundary, which can include dipolar, exchange and anisotropy pinning fields. Here, we are presenting an approach for the determination of the Heisenberg exchange, where we measure the spin-wave dispersion with BLS in the Damon-Eshbach and in the backward volume geometry, where the magnetic field is applied perpendicular and parallel to the spin-wave propagation direction, respectively. By simultaneously fitting the two spin-wave branches, we can determine A_{ex} and in addition the saturation magnetization M_s and the magnetic thickness t [5].

We sputter deposited a series of substrate/Ta(3 nm)/Cu (5 nm)/$Co_{90}Fe_{10}(t)$/Cu(2.5 nm)/Ta(3 nm) samples with t=1.4 nm, 3.0 nm and 14.0 nm. We measured FMR over a broad frequency range with the external magnetic field in-plane and perpendicular to the sample plane to determine the spectroscopic splitting factor g and the out-of-plane magnetic anisotropy. We obtained the thickness of the magnetic deadlayer t_D=0.05±0.01 nm from room temperature SQUID magnetometry. We deposited an additional sample with a 5 nm thick $Co_{90}Fe_{10}$ layer to increase the accuracy for these measurements. We then determined M_s of the samples using the corrected thickness for the magnetic layer.

We carried out BLS measurements in the Damon-Eshbach and the backward volume geometry with a laser wavelength of 532 nm. The applied magnetic field was $\mu_0 H = 150$ mT. We changed the angle of incidence to access spin-waves with a range of different wavevectors. We fitted the data for both spinwave branches simultaneously with the dispersion equation, see Fig.1, where t, A_{ex} and M_s were fitting parameters:

$$f(k,H,\phi,t) = \frac{\mu_0\mu_B g}{h}\sqrt{\left(H - H_k + \frac{2A_{ex}}{\mu_0 M_S}k^2 + \mathcal{N}M_S\left(\frac{1-e^{-k\,t}}{k\,t}\right)\right)}$$

$$\cdot\sqrt{\left(H + \frac{2A_{ex}}{\mu_0 M_S}k^2 + \mathcal{N}M_S\left(1 - \frac{1-e^{-k\,t}}{k\,t}\right)sin^2(\phi)\right)},$$

where f is the spin-wave frequency, H_k the anisotropy, h is Planck's constant, ϕ the angle between the magnetization and the spinwave propagation direction, g is the spectroscopic splitting factor, μ_0 is the

vacuum permeability, μ_B the Bohr magneton, k is the spin-wave wavevector and $\mathcal{N}$ an approximate perpendicular demagnetizing factor for ultrathin films.

We measured the temperature dependence of the magnetic moment with SQUID magnetometry and fitted the data with the Bloch $T^{3/2}$-law, see Fig. 2. We then used mean field theory to determine the room temperature value for A_{ex}.

The results for the exchange parameter determined from magnetometry and BLS are in close agreement. The weighted mean for the BLS and SQUID results for all three films are $A_{ex}^{BLS} = 21.020 \pm 0.050$ pJ/m and $A_{ex}^{SQUID} = 21.488 \pm 0.052$ pJ/m. The BLS measured value for the 14 nm thick film $A_{ex}^{BLS} = 22.4 \pm 2.4$ pJ/m is close to the value obtained by Neutron scattering for bulk $Co_{92}Fe_8$ of $A_{ex}^{Neutron} = 22.8$ pJ/m, whereas $A_{ex}^{SQUID} = 21.6 \pm 0.1$ pJ/m [6].

The thicknesses from the fits of the spin-wave dispersion are t=1.36±0.03 nm, 3.30±0.07 nm and 13.93 ± 0.25 nm, respectively. This is in good agreement with the $t_D = 0.05 \pm 0.01$ nm determined from the thickness series.

Finally, the values for M_s obtained from the BLS measurements are close to the SQUID magnetometry values, starting from the thinnest film: $\mu_0 M_s^{BLS} = 1.881 \pm 0.002$ T, $\mu_0 M_s^{SQUID} = 1.769 \pm 0.025$ T, $\mu_0 M_s^{BLS} = 1.769 \pm 0.007$ T, $\mu_0 M_s^{SQUID} = 1.804 \pm 0.048$ T and $\mu_0 M_s^{BLS} = 1.856 \pm 0.013$ T, $\mu_0 M_s^{SQUID} = 1.869 \pm 0.043$ T.

In summary, our measurements demonstrate that BLS spectroscopy can provide accurate results for the saturation magnetization, Heisenberg exchange and thickness and has the potential for non-destructive wafer level measurements. This technique is applicable to even thinner films and can possibly be multiplexed by using multiple laser beams for faster sample throughput.

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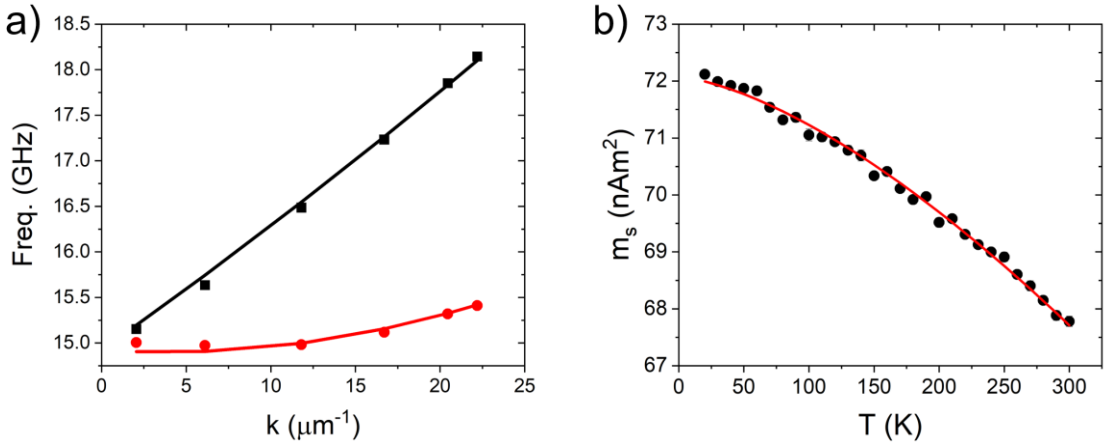
Figure 1: a) Spinwave dispersion for the 3 nm thick film in the Damon-Eshbach (black) and backward



volume geometry (red). The solid lines are fits with the spin-wave dispersion equation. b) Temperature dependent magnetic moment for the 1.4 nm thick film. The red line is a fit with the Bloch $T^{3/2}$-law.

Skyrmion-Excited Spin Wave Fractal Network

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Introduction

Magnetic skyrmions are a type of chiral spin texture which is of interest due to their fundamental properties and for advanced spintronic applications.[1] These magnetic structures consist of a coplanar continuous wrapping of the spins into a closed coplanar loop with a core and fencing perimeter which are oriented in opposite, out-of-plane directions. The coplanar loop can itself have two orientations, with the spins on the loop oriented along the radial direction (called Néel-type) or along the azimuthal direction (called Bloch-type). Stacking these structures generates the 3D skyrmion tube. The very specific loop, core and perimeter structure gives the skyrmion a non-trivial topology. Functionally, this means that there is an energy barrier to the creation or destruction of the skyrmion and that skyrmions can interact without merging.

The chiral winding of the skyrmion is atypical for magnetic materials since it generates a large exchange energy. Early skyrmion materials overcome this energy with a competing Dzyaloshinskii Moriya interaction (DMI).[2] Recent works performed on Gd/Fe multilayer thin films[3, 4] have demonstrated a twist on the traditional skyrmion configuration, achieving stability by dipolar interactions, rather than DMI. The increased dipolar interactions in-turn generate flux closure domains at the surface of the film, e.g. the end of the skyrmion tubes. In these flux closure domains, the magnetic moments necessarily orient radially from the core to the perimeter, with an orientation that is opposite on opposite ends of the skyrmion tube, following the dipolar fields. This structure closely resembles a Néel-type skyrmion. A hybrid skyrmion tube can thus be described as a stack of Néel/Bloch/Néel features. The Néel structures reduce the stray magnetic fields in the system, reducing the magnetostatic energy and increasing the skyrmion stability. In the discussed works, we use neutron scattering, as a probe of nanoscale magnetic structure, to investigate hybrid skyrmion systems.

Forming an Ordered Skyrmion Lattice without DMI

The above description of the skyrmion as a chiral winding and skyrmion tube is accurate for a single skyrmion, however, in traditional systems the skyrmions form an ordered hexagonal lattice. In a lattice configuration, the magnetic configuration can alternatively be described as a 3-q helical structure, that is, three magnetic helices separated by 120°. The helical description more accurately describes the competition between the exchange and DMI energies as this competition exists everywhere within the sample. In the hybrid skyrmions, there is weak or no DMI, thus these structures can form as isolated islands, or clusters. For some applications, such as the dynamic fractal work discussed below, having closely packed skyrmions on an ordered lattice is ideal.

While skyrmions stabilized by dipolar interactions lack the ridged interaction (the exchange and DMI) which facilitates the hexagonal lattice in traditional systems, the dipolar fields do generate a repulsive interaction between hybrid skyrmions. Indeed, X-ray microscopy shows that the skyrmions form domains with hexagonal ordering. In this first work, we demonstrate a combined field sequence and tilting scheme which facilitates long-range orientation of the skyrmion lattice domains.[5] Using SANS, the skyrmion lattice and stability window is probed. These measuremens show that the hybrid skyrmions in Gd/Fe multilayers possess superior stability, spanning from 10 K to 325 K, and fields between -30 mT to 200 mT.

Determining the 3D Structure of Hybrid Skyrmions

The structure of the skyrmion provides the non-trivial topology and also the improved stability for the case of the hybrid structure. Understanding the structure of the hybrid skyrmion may provide insights which can be leveraged to improve the skyrmion stability. However, experimentally determining the structure of the skyrmion is exceedingly challenging due to the nanoscale nature of the structure, its magnetic-only contrast, and the fact that the skyrmion tube is buried within the materials. Most techniques for visualizing magnetic structures have limitations which prohibit their use here, including surface sensitivity, or a projected signal. Recent works have had success in needle-like sample of traditional skyrmions, but similar techniques would be challenging to implement in a film.

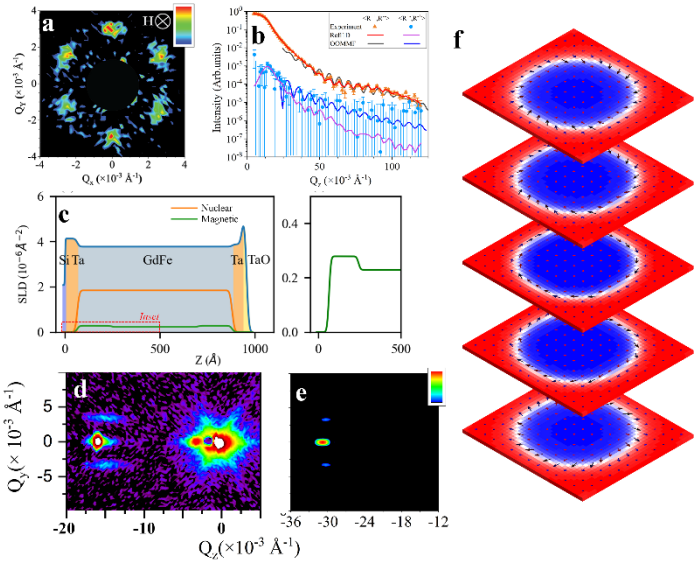

Figure 1: (a) SANS patterns from skyrmions in Gd/Fe thin-films (b) PNR reflectometry pattern, (c) converged depth profile (d) GISANS measurement, (e) simulated GISANS, and (f) converged model of the 3D structure.

Using a combination of polarized neutron reflectometry (PNR), small angle neutron scattering (SANS) and grazing-incidence SANS (GISANS), the 3D structure of the hybrid skyrmion is determined in a thin-film.[6] Analysis was performed by modeling the system with micromagnetics, then calculating the scattering pattern from the model and comparing the experimental and simulated patterns. The model was iteratively changed until the two patterns converged. The resulting model is thus grounded within the well-established physics of magnetism, and confirmed by the experimental scattering results. The simulations provide unique insights into the structure of the hybrid skyrmion. Among these insights, the in-plane winding of the hybrid skyrmion is wider at the top versus the middle, making it attractive to attribute these regions to the Néel and Bloch regions, respectively. However, the wall thickness and in-plane angle of the domain wall are incommensurate, with the Néel and Bloch regions instead evolving continuously along the length of the skyrmion tube.

Skyrmion Dynamics and a Dynamic Spin Wave Fractal

The third work discussed here investigates the magnetic dynamics of the skyrmion and associated spin waves while performing in-situ SANS with ferromagnetic resonance (FMR).[7] Specifically, using a static magnetic field along the skyrmion tube and a dynamic (GHz frequency) excitation field applied orthogonal to the skyrmion tube, dynamic gyration modes are excited. The SANS pattern shows relatively little change in the ordering of the skyrmion lattice, however, at the resonance condition, a large anomalous scattering signal is observed at exceedingly low angles (low-q). The intensity of the anomalous scattering grows to be >5× larger than the coherent diffraction from the skyrmion lattice. This signal is sharply peaked at the resonant condition, diminishing at both higher and lower fields for a fixed excitation frequency, allowing it to be attributed to the magnetic dynamics.

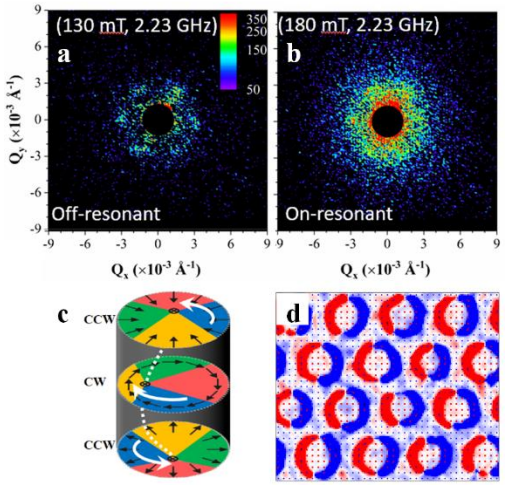

Figure 2: SANS patterns from skyrmions in Gd/Fe thin-films with in-situ excitation, taken (a) off-resonance and (b) on resonance. (c) Illustration of one of the skyrmion dynamic modes. (d) simulation of the dynamic skyrmions and the spin wave fractal network.

The model which best fits the anomalous scattering is a mass-fractal model. This model is used to describe statistical fractals, such as polymer chains, which are constructed from identical fundamental building blocks and have multi-scale self similarity. The structure of the fractal is found to have a dimensionality of ≈2, a fundamental building block size of ≈20 nm, and a cutoff length of ≈100 nm at resonance. Considering the correlation with the dynamics, spin waves ejected during gyration are implicated in the formation of this structure. This further implies that the spin waves are generated with a well-defined periodicity, as suggested by recent simulation works. The cutoff length approximately matches the skyrmion edge-to-edge distance indicating that the skyrmions may be coupled through these spin waves. Noting the inherent sensitivity of fractals to their generating mechanics, this structure is expected to be highly sensitive to the structure of the skyrmion lattice, making it a promising feature for stochastic computing technologies.[8]

Conclusions

These works together form a body of work focused on the use of neutrons to achieve new insights into hybrid skyrmions, including their structure, dynamics and the spin waves from those dynamics. Understanding these features presents new opportunities for technologically relevant skyrmion technologies, including enhanced stability and unique computing architectures.

Acknowledgements

This work was supported by the DOE (Award DE-SC0021344), NSF (Awards 2105400, DMR- 2010792, and DMR-1508249). Neutron research was performed on GPSANS at the High Flux Isotope Reactor, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory, and the VSANS part of the Center for High Resolution Neutron Scattering, a partnership between the National Institute of Standards and Technology and the National Science Foundation.

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The evolution of models of FePt

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The University of York, UK

The binary alloy FePt has long been of interest and has seen an explosion of research investigations following its development as the most likely candidate for Heat Assisted Magnetic Recording (HAMR) because of its low Curie temperature and high magnetocrystalline anisotropy. It is especially interesting because of the origin of the anisotropy in the strong spin-orbit coupling of Pt and the requirement of Fe to provide the magnetic structure. Initially it was thought likely that the symmetry breaking usually required to provide high anisotropy was the fct structure of FePt with contraction along the c-axis. However, the pioneering work of Oleg Mryasov [1] showed that the large anisotropy was a result of the layered $L_1 0$ structure of the alloy. The aim was to develop a classical spin Hamiltonian for spin dynamics models, specifically for HAMR. This was complicated by the fact that the Pt could not be treated as independent degrees of freedom. Instead they were found to be proportional to the exchange field from the Fe which was shown to lead to a spin Hamiltonian dependent only on the Fe degrees of freedom, with modified exchange and, importantly, an exchange-driven 2-ion anisotropy whose temperature dependence explained the experimental observations [2,3]. Based on this model I will outline calculations which gave important insight into the HAMR process. In particular the simulations showed that the elevated temperatures associated with HAMR introduced a new factor in the design process, specifically the requirement of a write field sufficiently large to avoid thermally induced backswitching, a factor later included in a magnetic 'quadrilemma'[4]. A second important factor is the existence of a novel 'linear reversal' mechanism which will be shown to be essential to achieving high switching probabilities in HAMR.

More recently, the nature of the main assumption of the Mryasov spin Hamiltonian has been under investigation, specifically that leading to the removal of the Pt degrees of freedom. This is an approximation which is valid for perfectly ordered systems sufficiently large to avoid finite size effects. Grain sizes in HAMR media are aiming, in the ASRC design for media for storage densities of 4.7Tbit/sq in, for grain sizes of 3.8nm. Clearly a model taking proper account of surface effects is increasingly important. Ma and Dudarev [5] and Ellis et. al. [6] have developed an approach in which the Pt degrees of freedom are introduced into the model using a Landau-like free energy. The physical basis is similar to the Mryasov model in that the Pt moments are considered to be induced by the exchange field from the Fe. I will outline this model and some recent developments which reveal unexpectedly large fluctuations of the Pt moment. I will also outline the fundamental limitations of the approach and finish with some potential areas for future development.

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Multiphysics micromagnetic models and solvers

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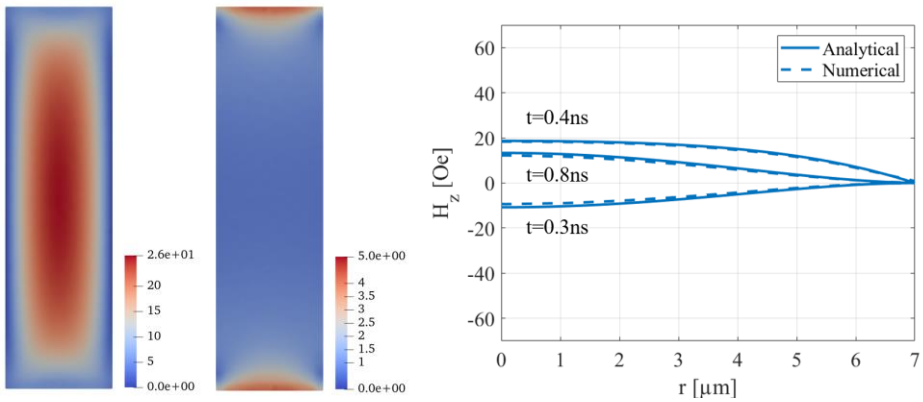
Magnetization dynamics is described by the Landau–Lifshitz–Gilbert equation (LLGE), which includes effective torques related to various physical interactions. Conventional interactions include the exchange, applied, anisotropy, and magnetostatic field components. Additional effective field and torque components play an important role in the behavior of magnetic materials and devices. In this work, we describe how micromagnetic solvers for LLGE can be coupled with solvers for other physics types. Specifically, we present multiphysics solvers that couple the magnetization dynamics described by LLGE with Maxwell's equations to describe eddy current effects, equations for spin polarized currents for describing spin transfer torque and spin Hall effects in bulk and at interfaces, and elastic equations describing effects of magnetoelasticity.

The presentation starts with reviewing the finite element method (FEM) in micromagnetic modeling. The description includes implicit time integration methods, efficient effective field evaluation methods, methods to model periodic structures, and discretization. Then, approaches for coupling LLGE with other physics types are introduced. As a general approach, at each time step, different physics types are solved concurrently, and their coupling is achieved by exchanging the relevant quantities on the fly. Following the description of the LLGE FEM procedures, procedures for the other physics types are presented.

Solving Maxwell's equations beyond its magnetostatic approximation becomes important as the operating frequency and structure size increases. In such cases, electrodynamic effects, such as eddy currents, must be accounted for. We discuss FEM and integral equation formulations for Maxwell's equations and present an approach allowing truncating the computational domain to any arbitrary size, e.g., eliminating a need for having an airbox, which is typically required in such cases. To address this point, we present a two-step approach. In the first step of the approach, we calculate the magnetic field assuming corresponding magnetic scalar potential to be zero on the outer boundary of the computational domain. In the second step, we correct this solution by calculating the static field generated by the effective surface magnetic charges on the outer boundary obtained based on the domain truncation in the first step. We implement the approach in a FEM code and integrate it with the FastMag micromagnetic solver [1]. Figure 1a shows the total and correcting eddy field for a case of no airbox. Figure 1b shows the accuracy of the results.

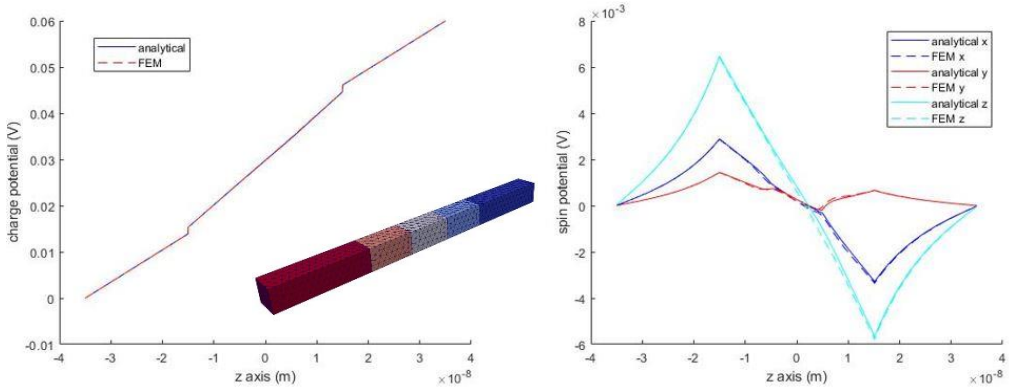
Micromagnetic modeling of spin polarized current effects is important for a set of applications in spintronics. Drift diffusion like models [2-5] have an appeal due to their ability to describe complex spin behaviors. We show that the Valet-Fert and drift diffusion models can be unified in terms of numerical modeling, which allows using the Valet-Fert related experimental material parameters in the drift diffusion model as well as including interfacial and bulk torques in ferromagnetic layers. We also include spin accumulation generated by the spin Hall effect and anomalous Hall effect for non-magnetic and ferromagnetic layers. Figure 2 shows an example of a solution verification for a 5-layer structure.

Strain-induced micromagnetic phenomena play an important role in a number of cases, e.g., magnetostriction effects or coupling of elastic waves with the magnetization dynamics. We present formulations for coupled micromagnetic and elastic solvers. We also present a study of strain-induced anisotropy in interfacial Dzyaloshinskii-Moriya interactions (DMI) (Fig. 3a). We employ Levy-Fert's analytical spatial model [6] to describe the DMI and derive a quantum Hamiltonian for the system. Using the linear spin wave theory [3], we obtain the spin wave dispersion relations as a function of the DMI anisotropy in the high-frequency approximation (Fig. 3b). We implement the formulation in finite difference and FEM based coupled micromagnetic-elastodynamic codes providing solutions for the magnetization, stress, and velocity. Using this formulation and code, we investigate the dynamical properties of systems with elastically induced anisotropy of DMI. The interplay between magnetoelastic effects provides a rich landscape for studying emergent phenomena such as spin waves, skyrmions, and domain walls.



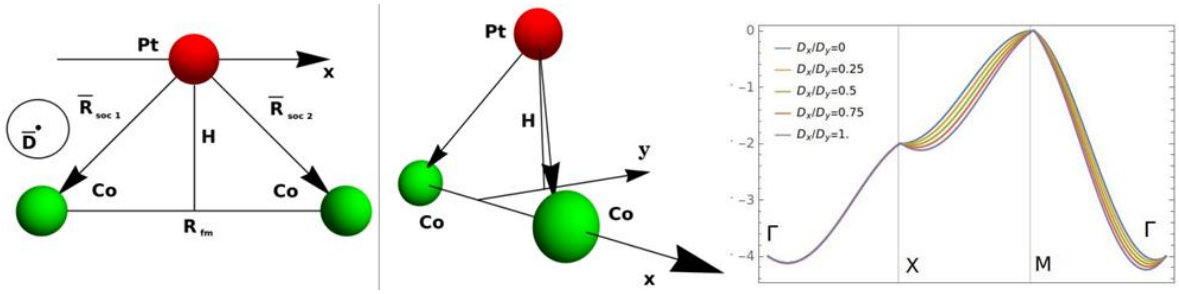
(a) (b)

Figure 1: (a) Total and correction eddy field for a test case of a cylinder driven by a dynamic axial magnetic field; (b) the axial eddy field dependence showing matching of the FEM based and analytical results.



(a) (b)

Figure 2: Comparison between analytical and FEM solution of the unified spin diffusion model. Inset in (a) shows the considered 5-layer structure with three magnetic layers separated by two non-magnetic layers. (a) Charge potential vs. z and (b) spin potential for the numerical and analytical solutions.



(a) (b)

Figure 3: Atomic triangle formed on a CoFe-Pt interface; (b) dispersion relation from the linear spin wave theory for the Γ−X−M−Γ path.

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Magneto-optics, revisited

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Two aspects of magneto-optics are reviewed that have hardly been considered in the past: (i) For MOKE magnetometry it will be shown that the obtained hysteresis loops need to be interpreted very carefully as they are measured locally, determined by the internal (not applied) field and local magnetization processes [1]. (ii) For wide-field MOKE microscopy numerous magneto-optical effects will be discussed that lead to intensity-based domain contrast in the absence of analyser and compensator. This includes the Transverse Kerr effect, a novel 45°-dichroic effect (Oppeneer effect), the Magnetic Linear Dichroism effect, and the Dichroic Gradient effect. All these effects require linearly polarized light for illumination. A further effect is the Magnetic Circular Dichroism effect that requires circularly polarised illumination.

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A friendship and collaboration that started with Co/Ni

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Co/Ni is a remarkable material widely studied for its applications in spin-transfer torques, pioneered by Eric Fullerton and his collaborators [1,2]. This talk presents our research on Co/Ni multilayers and nanostructures, focusing on their role in advancing our understanding and applications of spin-transfer torques. The key characteristics of Co/Ni include strong perpendicular magnetic anisotropy, large spin-polarized currents, reasonably low magnetic damping, and tunable magnetic properties through multilayer configurations with varying Co and Ni thicknesses. Our research findings encompass several areas: 1) the discovery of sub-nanosecond spin-transfer torque switching and identification of an optimal pulse length that minimizes energy consumption in magnetization reversal [3], 2) utilizing Co/Ni as a spin-polarizing layer to demonstrate spin-transfer induced precessional magnetization reversal of in-plane magnetized free layers and switching with 200 ps duration current pulses [4], 3) investigating nonlinear effects in spin-torque ferromagnetic resonance [5], and 4) studying Co/Ni based spin-oscillators [6,7]. The significance of these findings lies in their demonstration of several fundamental characteristics of spin-transfer torque dynamics. Another very significant aspect, particularly in the context of this celebratory symposium, is that our research on Co/Ni has led to a long-term collaboration and friendship with Eric, rooted in his generous sharing of samples, knowledge, and ideas.

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Thursday August 31st

9:00 – 9:25
Illuminating Hidden Symmetries in Topological Insulator Thin Films
George De Coster
9:25 – 9:50
Effect of magnetic phase transition on spin Hall angle
Biswajit Sahoo
9:50 – 10:15
Antiferromagnetic Spintronics: Past, Present, and Future
David Lederman
Coffee break: 20 minutes
10:30 – 10:55
Twisted light and topological structures of spontaneous symmetry breaking in nano-ferroics
Edwin Fohtung
10:55 – 11:20
X-raying topological spin textures in space and time
Peter Fischer
11:20 - 11:45
Cr-based bulk to nano fundamental research
Aletta Prinsloo
11:45 – 12:10
Static and dynamic correlations of stripes and skyrmions in Fe/Gd thin films
Sujoy Roy
12:10 AM - 2:00 PM: lunch & posters
2:00 - 2:25
Ultrafast dynamics of FePt nanoparticles
Herman Durr
2:25 - 2:50
Unraveling optically induced ultrafast dynamics of nanoscale magnetic textures
Roopali Kukreja
2:50 - 3:15
Magnetostrictive Evolution of Singular Anisotropic Magnetoresistance in Topological Metals
Matt Gilbert
3:15 - 3:40
FeRh in multifunctional exchange spring thin films
Tom Thomson
Coffee break: 20 minutes
4:00-4:25
Impacts of the half-skyrmion spin topology, spin-orbit torque, and dynamic symmetry breaking on the growth of magnetic stripe domains

Jeff Brock

4:25 – 4:50

GHz and sub-THz magnonics using ferro- and anti-ferromagnetic insulators

Romain Lebrun

Illuminating Hidden Symmetries in Topological Insulator Thin Films

Authors are cited in CAPITAL Letters with their initials followed by their last name in Calibri 12 centered like in the following:
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We observe enhanced three-fold symmetric helicity-dependent topological photocurrents using time-domain THz spectroscopy in epitaxially-grown Bi2Se3 with reduced crystallographic twinning. It is established how twinned crystal domains introduce competing responses that obscure inherent nonlinear optical responses of the intrinsic crystal structure. Minimizing this defect reveals strong nonlinear optical response currents whose magnitude and direction depend on the alignment of the excitation to the crystal axes and follow the three-fold rotational symmetry of the crystal structure. Notably, the azimuthal dependence of the photoresponse persists for helical excitations -- an unprecedented result we attribute to the photon drag effect, where the photon momentum acts as an applied in-plane field that is stationary in the laboratory frame. Additionally, the sign of the resultant THz signal inverts when the helicity of incident light is switched from right to left circularly polarized, indicating a reversal of the photocurrent. Our results demonstrate that even extended domain defects can obscure intrinsic physical processes, making the study of single domain thin films crucial to the observation of phenomena that couple topological order and crystal symmetries.

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EFFECT OF MAGNETIC ORDERING ON THE SPIN HALL ANGLE OF EPITAXIAL HO(*0001*) THIN FILMS.

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The operation of numerous spintronic devices are enabled through spin currents and thus, it is important to study how the generation, polarization and transmission of spin currents can be controlled by the local magnetic/electronic environment. Holmium is a rare earth metal which undergoes a paramagnetic to anti-ferromagnetic (AFM) transition at T_N=131K and an AFM to ferromagnetic (FM) transition at T_c=20K. The AFM phase is characterized by an incommensurate spin helix in which the average moments are ferromagnetically aligned within the basal planes but rotate from plane to plane along the *c* axis with an average turn angle varying from 50^0/layer at T_N to to 30^0/layer at T_C . Ho is further expected to have a good charge to spin conversion efficiency owing to its high atomic number and initial results of ploy-crystalline Ho films at room temperature show a spin Hall Angle (SHA) of 0.14[1]. Here, we explore the SHA of epitaxial Ho thin films in the paramagnetic, AFM and FM phases to observe the effect of magnetic ordering on the generation of spin current. We deposited epitaxial Ho (*0001*) using MgO(111) as a substrate with a 3nm W(*110*) as a seed layer and confirm the different magnetic phases via magnetometry and transport measurements. We create the following thin-film stack: MgO(111)/W(3)/Ho(10)/W(1.5)/Py(7)/W(1.5) (where the thicknesses are in nm) and study the SHA of Ho via spin torque ferromagnetic resonance experiments. We systematically vary the temperature down to 70K to study the charge to spin conversion efficiency. By relating various magnetic parameters such as effective magnetization, gilbert damping and SHA at various temperatures, we explore how the magnetic ordering affects the spin dynamics in this system.

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Antiferromagnetic Spintronics: Past, Present, and Future

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In his 1970 Nobel Prize lecture, Louis Néel famously wrote that antiferromagnetic materials "are extremely interesting from the theoretical viewpoint, but do not seem to have any applications" [1]. Although Néel was an excellent physicist and predicted the existence of antiferromagnetic materials, his assessment regarding the technological impact of antiferromagnets was not accurate. Starting with the application of antiferromagnetic materials in spin valve technology, where an antiferromagnetic layer is used to pin one of the ferromagnetic layers [2], antiferromagnets have also been used to make thermally-stable magnetic media [3] and to stabilize spin-transfer torque devices [4], among other applications. More recently, the spintronic properties of antiferromagnets themselves have been studied with the aim of making high frequency (THz) devices which are relatively stable under external fields due to their small net magnetization [5, 6]. In my talk, I will discuss how past work on the exchange bias used to pin ferromagnets using antiferromagnetic materials can be put in context with the idea of the recently proposed altermagnetism [7] where the time-reversal symmetry is broken due to the different local spatial symmetries of the antiferromagnetic sublattices. I will also discuss how insulating antiferromagnets can be used to generate electromagnetic signals using spin-pumping, which takes advantage of the spin Hall effect in layers with large spin-orbit coupling in proximity to antiferromagnetic insulator [8, 9]. Finally, I will also discuss the possibility of using antiferromagnetic insulators to interact with topological materials to break time reversal symmetry of the topological states [10], and thus induce a magnetoelectric effect and chiral edge modes [11].

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Twisted light and topological structures of spontaneous symmetry breaking in nano-ferroics

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Introduction: In the realm of optics, the control and manipulation of light have undergone remarkable advancements, allowing for the exploration of its various degrees of freedom, such as polarization, phase, amplitude, spin, and orbital angular momentum. This expanded control has given rise to the generation and application of structured light fields, including tailored light, shaped light, and sculpted light. These advances have transformed light from traditional two-dimensional transverse fields to four-dimensional spatio-temporal structured light and multidimensional quantum states, extending beyond orbital angular momentum to encompass control over all degrees of freedom. This paper explores the emerging synergy between structured light and nanoscale topological structures in ferroic materials, uncovering their implications for photonics, materials science, and device engineering.

Orbital Angular Momentum and Optical Vortices: A rigorous analysis of the electromagnetic field reveals that the total angular momentum of any light field can be decomposed into spin and orbital contributions. In free space, the Poynting vector, which describes the direction and magnitude of momentum flow, is the vector product of the electric and magnetic field intensities. When dealing with helical phase fronts, the Poynting vector exhibits an azimuthal component, resulting in an orbital angular momentum parallel to the beam axis. These beams, containing optical vortices, possess a circulating momentum about the beam axis. Notably, the orbital angular momentum is independent of the beam's polarization and arises from helical phase fronts where the Poynting vector deviates from its parallel alignment with the beam axis, following a spiral trajectory around the axis at any fixed radius within the beam.

The interplay between structured light, characterized by its topological singularities such as optical vortices and phase singularities, and ferroic materials has emerged as a promising avenue for controlling and manipulating emergent properties in condensed matter systems. We shall discuss our recent studies that leverages the interaction of twisted light as both a pump and probe with nano-ferroics, including magnetic, ferroelastic, and 2D Rashba ferroelectrics nanostructures, to create and control topological defects. The emergent topological structures are probed using operando coherent X-ray scattering and imaging techniques. By harnessing structured light, we enable and manipulate nanoscale topological structures in ferroic materials, leading to potential advancements in domain engineering, spintronics and new characterization tools.

X-raying topological spin textures in space and time

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Spin textures and their dynamics are key to understand and control the properties, behavior and functionalities of novel magnetic materials, which can impact the speed, size and energy efficiency of spintronics. Topological spin textures have recently attracted significant scientific interest and led to intense research addressing a broad spectrum of challenging scientific and technological questions on magnetic skyrmions and Hopfions [1].

Advanced characterization tools that provide magnetic sensitivity to spin textures, disentangling the role of individual components in heterogeneous material at high spatial resolution, ultimately at buried interfaces and in all three dimensions [2], and at high temporal resolution to capture the spin dynamics across scales, are required to address those questions, and are therefore of large scientific interest. Various magnetic soft X-ray spectro-microscopies [3] using polarized soft x-rays provide unique characterization opportunities to study the statics and dynamics of spin textures in magnetic materials combining X-ray magnetic circular dichroism (X-MCD) as element specific, quantifiable magnetic contrast mechanism with spatial and temporal resolutions down to fundamental magnetic length, time, and energy scales.

In this talk, I will show our recent studies on the statics and dynamics of magnetic Hopfions, which are spin textures that can only exist in 3D. In addition to the topological winding number which are characteristic for magnetic skyrmions, they exhibit an additional topological linking number and can be viewed as twisted skyrmion tubes. Using a combination of soft x-ray magnetic microscopies we confirmed the creation of Hopfions in tailored magnetic multilayers [4], with target skyrmions [5] being precursors as predicted from theory [6]. Micromagnetic simulation using high performance computing tools on the field dependence of Hopfion structures showed characteristic dynamics including a transition to a toron state around 60mT [7]. A 3D metrology of skyrmions using soft x-ray laminography shows a depth dependence of topology and chirality [8].

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Cr-based bulk to nano fundamental research

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Cr and its alloys constitute the architype of a class of systems that undergo magnetic phase transitions associated with the nesting of the electron and hole Fermi surfaces [1,2]. The beauty of the variety of properties observed in Cr based materials, finds its origin in the spin-density-wave (SDW) state, which forms when the electron and hole Fermi sheets overlap on cooling through the Néel transition, T_N [2]. In pure Cr the SDW is incommensurate (I) with the lattice, resulting in an ISDW phase [1]. As the Fermi surface is very sensitive to the electron concentration per atom (*e/a*), it is possible to adjust the relative sizes of the electron and hole Fermi surfaces through doping [2]. In general, doping with elements to the left of Cr, such as V, decreases the *e/a*, making the electron Fermi sheet smaller relative to the hole Fermi sheet. However, doping with elements to the right of Cr, such as Mn and 5*d* elements, increases the *e/a*, with an initial increase in the size of the electron Fermi sheet, resulting in an improved overlap between the electron and hole Fermi sheets and the formation of commensurate (C) SDW with the lattice [2]. The decrease in *e/a* normally results in a destabilization of SDW with a concomitant decrease in T_N, while increase in *e/a* results in an increase in T_N to a maximum, where a critical *e/a* is reached when optimum overlap of the electron and hole Fermi sheets occur. Following on, T_N decreases as *e/a* is further increased. This is seen in Cr with group 8-elements used as dopants [3]. Another mechanism used in tuning T_N, is that of electron-pair breaking, observed when using elements with an *e/a* similar to Cr for example with Mo as dopant [4]. However, there are exceptions to this simple rule, for example when Cr doping with Al and Ga, resulting in interesting magnetic phase diagrams and unexpected properties, such as Cr-Al alloys that become semiconducting at high enough dopant concentrations [2]. Hence, probing Cr alloys' SDW characteristics continues to be interesting due to the exceptional diverse behaviour observed, but understanding these also remains challenging. The SDW state contributes a large component, of magnetic origin, to nearly all the physical properties of Cr alloys [1,2]. This implies that once the fundamental role of the SDW contributions to these properties is understood, these alloys can be tailored to give specific desired characteristics, including particular thermal expansion and elastic constants for invar and el-invar materials, as well as particular electrical resistivity characteristics and much more. These alloys' adaptability provides endless opportunities for a vast range of promising applications for Cr based materials. In addition, from a purely scientific perspective, there is also renewed interest in the properties of dilute Cr alloys, particularly in their magnetic phase diagrams [5], quantum critical behaviour [6] and their role as spacer layers in magnetic multi-layered thin film structures [7] that forms the basis of many modern innovations.

Firstly, the richness in the variety of magnetic phases observed in Cr alloy systems [2] make investigations into their magnetic phase diagrams appealing. The theoretical canonical model is useful to explain the main features of the magnetic phase diagrams of these alloys, as well as many of the physical properties observed [2]. However, the addition of detailed aspects is required to explain many uncommon and unique features that is at present not fully understood. One such unusual aspect in magnetic systems has to be quantum criticalities that occur where an order parameter is continuously suppressed down to lowest temperature, typically 0 K, and an instability known as a quantum point is observed [5,6]. This suppression of the magnetic properties can be obtained through the tuning of various parameters, such as concentration, magnetic field or pressure [5,6]. Research on quantum

phase transitions led to the discovery of novel electronic ground states in magnetic materials and new concepts of low lying excitation spectra found in condensed matter systems [8].
Considering this new and interesting research field, the focus has during the last decade moved to extending the physical properties measured under extreme conditions in order to probe the SDW behaviour, study magnetic phase diagrams and quantum critical behaviour in these systems. Results obtained indicate various novel findings in the field of Cr alloys, including a newly proposed magnetic phase diagram for the Cr-Al system [9]. This system was further investigated through doping with Mo that is isoelectronic with Cr. This led to a study on the quantum critical behaviour in the Cr-Al-Mo alloy system and an investigation into SDW phonon coupling effects on the specific heat of Cr alloy systems [10]. In line with these types of investigations Mo doping of the Cr-Si alloy system was also probed as to gain greater insight into this system that showed most interesting characteristics [11]. These include a sharp first order ISDW to paramagnetic transition in certain concentration ranges, while continuous second order CSDW to paramagnetic transition is observed in another concentration region for the same alloy system. Results suggest [11] the existence of two critical points in a Cr-Si-Mo phase diagram: a suggested critical end point in the magnetic phase diagram of this system and suppression of the antiferromagnetism at a second critical point. This is the first time that this behaviour has been reported in Cr alloy systems.
In tandem work on the magnetic phase diagrams of Cr alloys with group-8 diluents [3] resulted in the completion of the phase diagrams of these alloys to much higher concentrations than previously reported. This opened new avenues for research into SDW antiferromagnetism, quantum criticalities and superconductivity in Cr alloys with group-8 diluents, not explored previously. Results obtained for the bulk Cr-Os samples confirmed the existence of a superconductivity dome in the magnetic phase diagram, as well as the coexistence of SDW antiferromagnetism and superconductivity in certain Cr based bulk samples [12].
Results on Cr-Ru-V give information on the role of SDW effects at 0 K on relationships between various physical properties [13]. Experimental results for the first time provided evidence that in Cr alloys the Seebeck coefficient can be used as a decisive parameter to characterize quantum critical behaviour [14]. These findings were supported by results on Cr-Re-V [15] and Cr-Ir-V [3]. An overview of all the properties of Cr alloys with group-8 diluents should result in a comprehensive overview of quantum critical behaviour in these alloy systems.
Giant magneto resistance in Cr-Fe-Mn alloys were observed together with spin-glass behaviour [16]. Work on additional Cr alloy systems, including Cr-Re-Mn, Cr-Si-Mn and Cr-Al-Mn alloys, showing possible spin-glass is underway and shows much promise.
Work on various magnetic phase diagrams contributes novel aspects to the field of magnetism in Cr alloys, emphasizing the need for similar and further studies to explore SDW and spin-glass behaviour, magnetic phase diagrams and quantum criticalities, as well as superconductivity and semiconductor behaviour in certain Cr alloy systems.
Secondly, as thin films and hetero-structures form the basis of modern structured materials, it is useful to probe the properties of Cr alloys in confined geometries [7]. These materials can then be tailored for specific applications in devices. Understanding of dimensionality effects and proximity magnetism is essential in gaining insight into the behaviour of magnetic structures. Initial work on thin films and hetero-structures focusing on Cr-Mn/Cr [17] and Cr-Ru/Cr [18] together with Prof Eric Fullerton, showed innovative results with evidence of SDW pinning and the effect thereof on the transition temperatures. Work on Cr-Al thin film studies drew parallels between the physical properties such as grain size, stress and the magnetic behaviours of these thin films [19]. This research gave insight into the SDW behaviour in confined geometries and contributed to a more fundamental understanding of the SDW behaviour. Work on Cr alloy thin films containing Si, Co, Mo, V and Re is presently underway in order to gain a deeper understanding of the behaviour of the SDW in confined geometries.

Thirdly, ventures into the fields of nano hetero-structures and particles have only started recently. Collaborative work on thermal simulation of magnetization reversals for size distributed assemblies of core-shell exchange biased nanoparticles [20] initiated work on nanoparticles. Chromite micro and nanoparticles are of current interest to study due to the magneto-structural coupling in the geometrically frustrated antiferromagnet, where structural distortion elevates the ground state degeneracy leading to a long-range magnetic order. Early studies focused on $A_{1-x}B_xCr_2O_4$ (*A, B* = Fe, Co, Ni, Cu, Mn, Cd, Zn, Ce) compounds. Considering combinations of *A* and *B* various compounds can be made, each with unique properties. Results of these studies [21, 22] indicate that control over the synthesis assist in obtaining smaller particles having uniform size and morphology. As magnetic properties are influenced by particle size, attention was given to obtaining smaller, mono-dispersed particles. One of the key parameters that was identified was the controlled calcination and suitable methods were probed to avoid particle agglomeration. AC susceptibility studies were also used to identify spin-glass behaviour and neutron diffraction studies linked the structure and magnetic properties [21,22]. Temperature dependent XRD studies also assisted in the understanding of the coupling between structure and magnetism. Small progress was made in moving into nanoparticle based thin films of these materials [23]. Results reveal a change of surface morphology upon Ni substitution in $CoCr_2O_4$ and demonstrate the complex nature of the oxidation states of Co and Ni. T_C of the $CoCr_2O_4$ is modified depending on the substrate and also with Ni substitution of Co site. Research on various synthesis methods, including green synthesis methods with traditional African plants, as well as capping to create core-shell particles, are also in progress to probe exchange bias and possible medical applications.

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Static and dynamic correlations of stripes and skyrmions in Fe/Gd thin films

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Understanding new topological states in condensed matter systems is a current research topic of tremendous interest due to both the unique physics, and their potential in applications. Skyrmions is an example of a topological phase that manifest in magnetic systems as a hexagonal lattice of spin vortices. We have shown that resonant X-ray scattering is a powerful tool to study skyrmions [1,2]. We have used resonant X-ray scattering to unravel a skyrmion lattice phase in a Fe/Gd multilayer (See Fig. 1). Fe/Gd shows a wealth of different magnetic textures and phases. It exhibits a well aligned stripe phase that evolves into a skyrmions phase depending on applied field and temperature conditions [2]. Within a small range of temperature and magnetic field we observed a hexagonal scattering pattern due to skyrmion lattice phase.

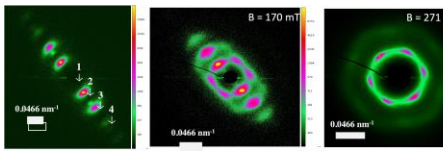

Figure 1. Resonant scattering images representing evolution of stripes (left) to skyrmions (right) as a function of

We have used coherent X-ray scattering to address the question of phase boundaries and underlying critical point in the context of stripe and skyrmion phases. Fluctuation and stochasticity are characteristics of material complexity. It is predicted that fluctuations play an important role in stabilizing the topological skyrmion phase in a magnetic system. Magnetic fluctuations that manifest as domain avalanches and chaotic magnetization jumps exemplify such stochastic motion and have been studied in great details. We performed Fourier space studies of avalanches using a soft X-ray speckle metrology technique. By using coherent X-ray scattering we obtained magnetic speckle patterns in the stripe and skyrmion phase of Fe/Gd thin film. We calculated pairwise autocorrelation coefficient of the data as a function of applied magnetic field and directly observed nanoscale stochastic behavior of the domains [3]. By analyzing the data within the framework of statistical mechanics we were able to characterize that the distribution of fluctuations could be collapsed to a unifying scale with parameters that are distinct in the stripes and skyrmions phases indicative of two separate universality classes. Spontaneous fluctuations in the time domain were studied using X-ray Photon Correlation Spectroscopy (XPCS) at LCLS2. We have developed a 2-pulse probe-probe based XPCS measurement at the LCLS that has the capability to measure fluctuation in the sub-nanosecond regime. We found existence of sub-nanosec fluctuations near stripe-skyrmion phase boundary. Finally, I will also show our recent studies on generation of soft X-ray orbital angular momentum beams and its application to magnetic materials.

Work supported by US DOE.

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Ultrafast spin-lattice coupling in FePt nanoparticles

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Magnetic nanoparticles such as FePt in the $L1_0$-phase are the bedrock of our current data storage technology. As the grains become smaller to keep up with technological demands, the superparamagnetic limit calls for materials with higher magneto-crystalline anisotropy. This in turn reduces the magnetic exchange length to just a few nanometers enabling magnetic structures to be induced within the nanoparticles. Here we describe the existence of spin-wave solitons, dynamic localized bound states of spin-wave excitations, in FePt nanoparticles. We show with time-resolved X-ray diffraction and micromagnetic modeling that spin-wave solitons of sub-10 nm sizes form out of the demagnetized state following femtosecond laser excitation. The measured soliton spin-precession frequency of 0.1 THz positions this system as a platform to develop miniature devices capable of filling the THz gap. The driving force for the formation of spin-wave solitons can be traced back to the ultrafast lattice expansion of the nanoparticles. Electron diffraction measurements show that Fe atoms start moving before the heavier Pt.

Unraveling optically induced ultrafast dynamics of nanoscale magnetic textures

Roopali Kukreja

Ultrafast optical control of magnetization has emerged as a new paradigm for the next generation memory and data storage devices. Numerous studies have been performed to understand the mechanism of transfer of angular momentum at such fast timescales. However, it has been recently recognized that spatial domain pattern and nanoscale heterogeneities can play a critical role in dictating the ultrafast behavior. These experimental findings have been possible due to recent advances in x-ray and extreme ultraviolet sources which combine the power of coherent x-rays with femtosecond (fs) temporal resolution. I will discuss some of the key studies performed at x-ray free electron lasers (XFELs) sources in the recent years which have shed light on the magnetic behavior at ultrafast and ultrasmall frontier. I will also describe some of our recent experimental results at European XFEL and FERMI where we uncovered symmetry-dependent behavior of the ultrafast response. Our results on the same sample with the same experimental conditions but different ground state (isotropic labyrinth domains vs anisotropic stripe domains) shows that the symmetry of magnetic texture dictates the magnitude and timescale of the ultrafast response. These results clarify the previous controversy in the literature for time-resolved magnetic studies for different samples showing distinct responses. We also utilized time-resolved magnetic scattering to test recent predictions of >10 km/s domain wall speeds. We observed fluence threshold dependence for distortions of diffraction pattern which are not seen for magnetization quenching, consistent with a picture of domain wall motion with pinning sites. Supported by simulations, we show that a speed of 66 km/s for highly curved domain walls can explain the experimental data. We thus show that these intriguing observations suggest preferential texture-dependent paths for the spin transport and provide us with a unique way to manipulate spin degrees of freedom.

Magnetostrictive Evolution of Singular Anisotropic Magnetoresistance in Topological Metals

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The ubiquity of topology within physics has been the source of much of our understanding of how symmetry both stabilizes and enhances observable phases of matter. Within condensed matter physics, the examination of topological phases of matter has led to the discovery of both new phenomena and the explication of previously overlooked physical responses that have been directly tied to the presence of a topology. The emergent importance of topological phases of matter has not only driven the examination of insulating, superconducting, magnetic, and heavy fermion materials. Of this diverse set of materials, magnetic materials, both ferromagnetic and antiferromagnetic, have been of particular interest due to the presence of broken time-reversal symmetry, that may lead to the presence of Weyl or Dirac fermions. Furthermore, the corresponding high Curie temperatures (T_c) well-known to exist in magnetic metals provides the possibility of finding and manipulating interesting topological phases at elevated temperatures.

In this work, we seek to clarify the interdependence of magnetic structure and topology by studying the interplay between magnetostriction and topology in elemental thin-film Holmium (Ho) using a combined experimental and theoretical effort. In our examination, we find C_6 rotationally symmetric discontinuous spikes in the anisotropic magnetoresistance (AMR) of the antiferromagnetic (AF) phase in Holmium when the magnetic field is aligned with the *a*-axis that are superimposed on a typical C_2 rotationally symmetric. As the temperature is increased and Holmium transitions to a conical ferromagnetic (FM) phase, the C_6 peaks begin to blend into a more dominant C_2 AMR. We explain this transition via magnetostrictive changes in the Holmium lattice that are associated with the applied in-plane as the material transitions from the AF phase to the FM phase.

FeRh in multifunctional exchange spring thin films

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The equiatomic alloy FeRh is of great scientific and technological interest due its highly unusual first-order antiferromagnetic (AF) to ferromagnetic (FM) meta-magnetic phase transition. This transition occurs at a technologically useful temperature, typically around $T_t \approx 370$ K, [1, 2] fig.1. This phase transition is accompanied by a substantial drop in electrical resistivity (≈30%) [3] and an isotropic increase in lattice parameter of ≈0.3% (≈1% volume expansion) [4]. Apart from the inherent scientific interest in studying the physics of phase transitions, this thermal magnetic behaviour has a wealth of potential applications in data storage [5] and a broad range of spintronics [6].

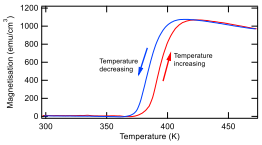

Fig.1: Thermal hysteresis of 50 nm thick

A particular feature of the meta-magnetic phase transition in FeRh is the ability to tailor its transition temperature T_t. Here several approaches can be employed, (i) applied magnetic field which results in T_t decreasing by ≈9 K/T [7], (ii) doping with a few atomic percent of elements such as Pd, Pt, Ir [2]; (iii) selective ion irradiation which provides the ability create patterned structures and arrays [8, 9]; (iv) control of the strain state [10, 11]. FeRh can also be used as a component in a heterogeneous multilayer where the other component layers can either be influenced by the FeRh phase transition, for example to form a magnetic exchange spring-like structure e.g. FePt/FeRh [5]; or where a layer can directly influence the FeRh such as a piezo-electric layer or substrate [12]. Here the coupled nature of the phase transition can be exploited so that actuating an increase in lattice parameter results in a change in magnetic properties.

This presentation will give some selected highlights of our work to understand the static and dynamic properties of FeRh and ion irradiated FeRh thin films [13, 14, 9, 15, 16, 17, 18, 19, 20, 21].Polarised neutron reflectivity (PNR) together with x-ray reflectivity (XRR) provides the ability to simultaneously determine the structure and magnetization of thin films as a function of film thickness (z- direction). Our results (and the results of others) show that there is a small region, close to the substrate where the magnetization is different to the “bulk” of the film and that films down to 5 nm in thickness can be successfully fabricated. Further PNR work on FeRh(10nm)/FePt(30nm) exchange spring systems, where the magnetization of the FePt was perpendicular to the plane and the FeRh magnetic moment

was in-plane, showed that the characteristic length for the exchange coupling δ increases due to the AF to FM phase transition. The exchange-mediated spin reorientation extends across at least the first 12 nm of FePt adjacent to an FeRh layer, representing an estimate of the thickness of an FePt layer in which the write field may be reduced by the exchange spring effect, fig.2.

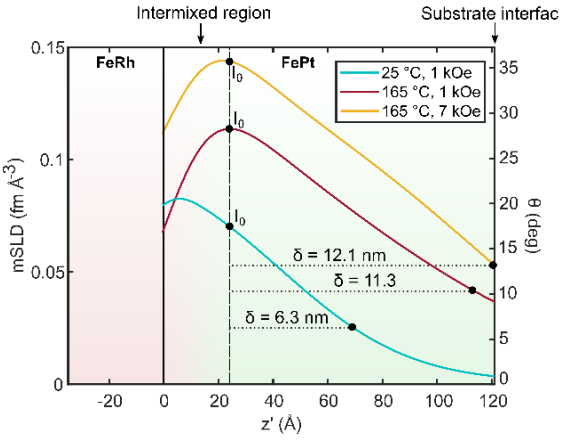

Fig.2: The decay of the mSLD through the depth of the FePt layer z', where $z' = 0$ is the FeRh/FePt interface and z' increases towards the substrate. The decay lengths d are characterised by the distance over which the mSLD reduces to $1/e$ of the value at $z' = 2.4$ nm (chosen to avoid effects

The potential of FeRh thin films as part of a multiferroic systems was investigated. Multiferroic systems with large magnetoelectric coupling constants offer exciting potential for next-generation devices for data storage, sensing and neuromorphic computing. Our work showed the presence of magnetoelectric coupling in a 21 nm thick FeRh thin film fabricated on a piezo-electric [001]-oriented PMN_{28}-PT_{72} single crystal substrate. The magnetoelectric effects were measured directly, rather than using the electrical resistivity as a proxy variable for magnetisation. XRD and VSM measurements with in-situ applied electric fields, demonstrated that magnetoelectric coupling is quenched at temperatures above ~100 °C, due to a gradual structural phase transition in the piezo-electric PMN-PT. We also showed a large strain remanence effect in the PMN-PT substrate, which limits the magnetoelectric coupling on successive cycling of the applied electric field. However, we demonstrated that through careful selection of the applied electric field range, it is possible to induce repeatable and deterministic all-electrical switching in this system over many electric field cycles, fig.3, although the effect is smaller than desirable for applications such as memresistors.

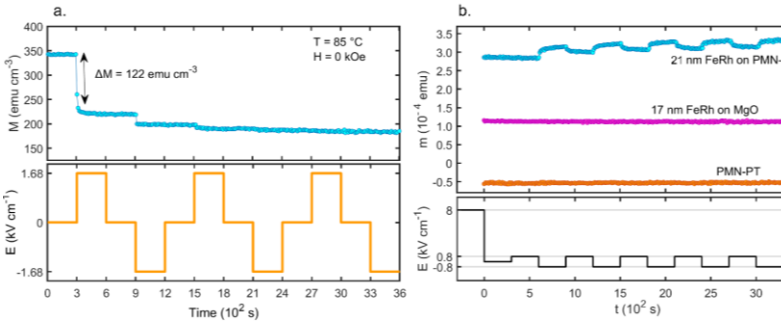

Fig.3: (a) The magnetisation of PMN-PT/FeRh as the applied electric field is switched between +1.68 kV cm-1 and −1.68 kV cm-1. On first increasing the electric field, the magnetisation is significantly reduced by the strain mediated magnetoelectric effect. Subsequent changes to the field produce diminishingly small changes to the magnetisation due to the strain being in a highly remanent state. (b) Repeatable switching in PMN-PT is demonstrated by applying an

The final section of the presentation will focus on work aimed at explore the ultrashort time scale structural dynamics of the FeRh metamagnetic phase transition [18]. This is a key element in developing a complete explanation of the mechanism driving the evolution from an antiferromagnetic to ferromagnetic state. Using an x-ray Free Electron Laser (x-FEL) with sub-ps resolution the time evolution of the (-101) lattice diffraction peak following excitation using a 35 fs laser pulse was measured, fig.4. The dynamics at higher laser fluence indicates the existence of a transient lattice state distinct from the high temperature ferromagnetic phase. By extracting the lattice temperature and comparing it with values obtained in a quasi-static diffraction measurement, we estimate the electron-phonon coupling in FeRh thin films as a function of laser excitation fluence. Our model shows that the transient state is paramagnetic and can be reached by a subset of the phonon bands.

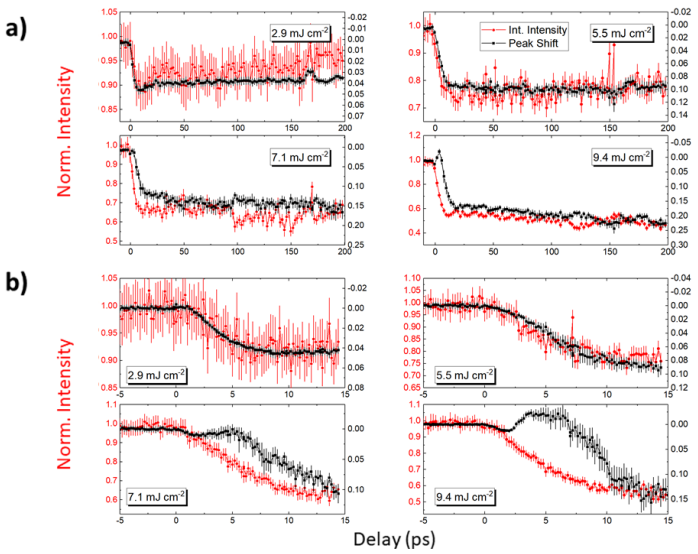

Fig. 4: TR-XRD of the (-101) FeRh Peak - a) Peak intensity and 2θ shift as a function of probe delay for the FeRh (-101) XRD peak. The extracted quantities show similar dynamics, initially decaying within 10-30 ps and recovering over 100's of ps. b) The same quantities focusing on the initial excitation up to 15 ps. For fluences 5.5 mJ cm-2 and above, the peak

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Impacts of the half-skyrmion spin topology, spin-orbit torque, and dynamic symmetry breaking on the growth of magnetic stripe domains

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The spin-orbit torque (SOT) generated when a charge current is passed through a heavy metal with sizeable spin-orbit coupling [1] has attracted significant research interest, given that it gives rise to the efficient movement of novel magnetic textures, such as chiral domain walls and skyrmions. Here, we discuss an experimental study of the SOT-induced motion of magnetic stripe domains in Pt/Co/Pt and Pt/Co/Ni/Pt thin-film heterostructures that possess an interfacial Dzyaloshinskii-Moriya interaction that favors the formation of chiral Neel-type domain walls [2]. In agreement with previous reports, we find that the domains exhibit a significant transverse velocity relative to driving force of the SOT. In these past works, this behavior was attributed to the Magnus force-like skyrmion Hall effect exhibited by the stripe domain topology (equivalent to that of a half-skyrmion) [3-5]. However, magnetometry and ferromagnetic resonance spectroscopy measurements suggest that the theoretically predicted transverse motion of stripe domains in our samples may be too large to be explained by the skyrmion Hall effect. Analytically modeling the steady-state dynamical reconfiguration of the half-skyrmion profile induced by SOT, we demonstrate how motion with similar directionality and symmetry as the skyrmion Hall effect can originate – further highlighting the sensitivity of SOT to the local orientation of the domain wall magnetization profile.

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GHz and sub-THz magnonics using ferro- and anti-ferromagnetic insulators

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Spin waves are collective spin excitations in a magnetically ordered material. In the classical regime, an intense field of research, named magnonics, targets spin-wave based computing relying on their integration as primary information carriers in logic and radiofrequency devices [1]. Beyond this aspect, spin-wave quanta, i.e., the magnons, can also bring promising perspectives for emerging quantum technologies [2]. In this talk, I will first present some of our recent efforts towards the development of on chip GHz analog devices using spin-waves (such as a spin-wave microwave delay or an amplifier [3]), and towards the observation and the control of magnon Bose-Einstein condensate [4].
Secondly, I will discuss how magnonics could benefit from the integration of antiferromagnetic materials that brings the prospect of devices operating at THz frequencies. Recent works highlighted how uncoherent magnons can propagate spin-information over long-distances insulating antiferromagnets [5,6]. However, efficiently excitation and detecting coherent magnons remains key challenging tasks to develop antiferromagnetic magnonic. Here I will show that one can use DC spin-current to detect antiferromagnetic resonance [7] and propagating spin-waves in a canted antiferromagnet [8]. Finally, I will highlight the possibility to achieve optically induced narrow band THz emission in antiferromagnetic materials using ultra-fast spin-currents [9]. These results highlight promising perspectives to develop antiferromagnetic phononic and opto-magnonic devices.

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Friday September 1st

9:00 – 9:25
Energy Storage and Information Storage – Converging Materials Science
Shirley Meng
9:25 – 9:50
Chiral magnetic spin textures in centrosymmetric and noncentrosymmetric thin film magnets
Sergio Montoya
9:50 – 10:15
Nanolasers: Dynamics and Phase Locking
Shaya Fainman
Coffee break: 20 minutes
10:30 – 10:55
Coherent coupling to a thicket of spin-wave modes in an ultrastrongly coupled microwave-magnon system
Michael Flatte
10:55 – 11:20
How to turn charge into spin
Axel Hoffmann
11:20 - 11:45
Shaken, not stirred: a recipe for magnetic switching via phononic resonances
Andrey Kiryliuk

Energy Storage and Information Storage – Converging Materials Science

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Solid state devices have been at the heart of modern-day technologies. Breakthroughs in fabrication and characterization have brought paradigm shifts in multiple energy related areas, including solid state energy storage, perovskite photovoltaics and neuromorphic memory devices, and beyond. All of these systems share a common feature: many of the materials used exhibit dynamic behavior driving large resistance change. However, these changes are accompanied by complex failure modes requiring dynamic observation for identification and subsequent failure prevention. Realization of all these technologies requires breakthroughs in our fundamental understandings of resistive phase change mechanisms in these devices, particularly their dynamic failure modes under realistic operating conditions.

Electrochemical memristors are often made of beam sensitive elements (e.g. light elements such as Li, Na, O or metastable phases), more importantly these meta-stable phases tend to only form upon operation of the devices, making them difficult to capture with conventional tools. Building on the past success, I will talk about the recent development in the fundamental understanding of reversibility in electrochemically driven resistive phase change materials through cryogenic operando analytical transmission electron microscopy (TEM) using our one-of-a-kind cryogenic biasing holder to slowing reaction kinetics of resistive switching processes while mitigating beam damage.

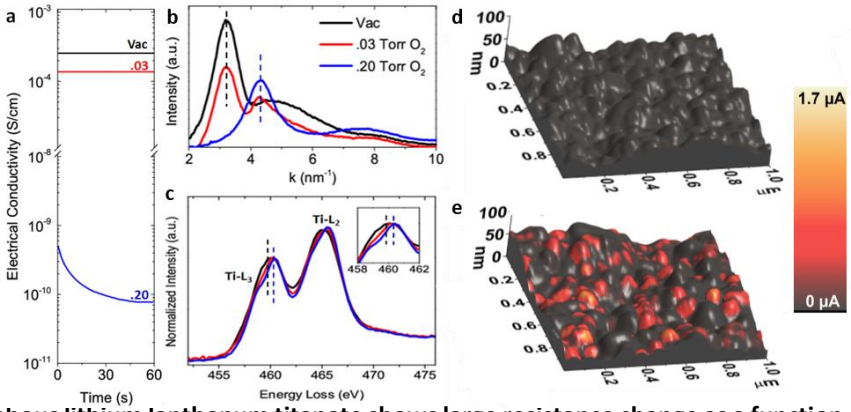

Figure 1: Amorphous lithium lanthanum titanate shows large resistance change as a function of oxygen processing conditions (a) attributed to reduced oxygen vacancy concentration indicated by radial analysis of electron diffraction (b) and (c) EELS. Lithium titanate undergoes a significant resistance state when transitioning between $Li_4Ti_5O_{12}$ (d) and $Li_7Ti_5O_{12}$ (e).

Chiral magnetic spin textures in centrosymmetric and noncentrosymmetric Fe/Gd-based thin film multilayers

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Designing materials capable of hosting chiral magnetic phases has been an active research area since the first experimental observation of magnetic skyrmions [1]. Through careful tailoring of the dipolar, anisotropy and symmetric exchange energies of a magnetic material, it is possible to form magnetic phases with an equal distribution of opposite helicity chiral spin textures [2], which on average yields a magnetic phase that is achiral; this magnetic phase can be described as exhibiting local chirality and global achirality. To realize magnetic materials that host a single global chirality, an additional magnetic energy is typically required to break the degeneracy of the two possible helicity distributions. Magnets with broken inversion symmetry can exhibit a sizeable antisymmetric exchange interaction, commonly known as Dzyaloshinskii–Moriya interaction (DMI) [3, 4], which favors the formation of chiral magnetic spin textures with a single local and global chirality [5, 6]. So far, the topological transition between global achiral to chiral magnetic phases is not well understood. In this talk, we will cover some of our recent work to design and stabilize intermediate chiral magnetic phases in Fe/Gd-based multilayers [7], and some of their interesting properties. We first demonstrate that competing dipole and domain wall energy can result in the formation of sub-100-nm skyrmions, bi-skyrmions and bubbles in Fe/Gd multilayers with centrosymmetric symmetry [2, 8]. Using a combination of transmission- and surface-sensitive microscopy techniques and micromagnetic simulations, we will show these dipole-stabilized skyrmions possess a complex 3D hybrid structure with Bloch- and Néel-components [Fig. 1(a-f)]. Then by surveying the field-induced evolution of chiral magnetic spin textures in a centrosymmetric Fe/Gd multilayer, as the perpendicular magnetic field is swept from one polarity to another, we show the field-stabilized magnetic phases undergoes local chiral morphological changes from the stripe phase to skyrmion lattice phase which ultimately enables the formation of two helicity dipole skyrmions under positive and negative applied fields [9]. On the second part of this talk, we focus on the local and global chirality changes that occur in the domain morphology when we systematically introduce broken inversion symmetry (via heavy metal Pt/Ir, Pt, and Ir interfaces) into an array of Fe/Gd multilayers. By carefully designing a non-centrosymmetric Fe/Gd-based multilayer, we can achieve a coexistence of opposite helicity chiral magnetic spin textures with unequal Bloch population distribution [7]. Figure 1(g) shows postprocessed LTEM image depicting the magnetic stripes with asymmetric population of left and right-helicity Block-lines. Then, using transmission-sensitive microscopy and transport measurements, we show the domain morphology in these non-centrosymmetric Fe/Gd-based multilayers dramatically rearranges under applied perpendicular magnetic fields which also yields interesting electromagnetic properties. Overall, the ability to locally control material properties symmetrically and asymmetrically across different thin-film layers of a

heterostructure presents a pathway to tailor competing local and global chirality effects in magnetic spin textures.

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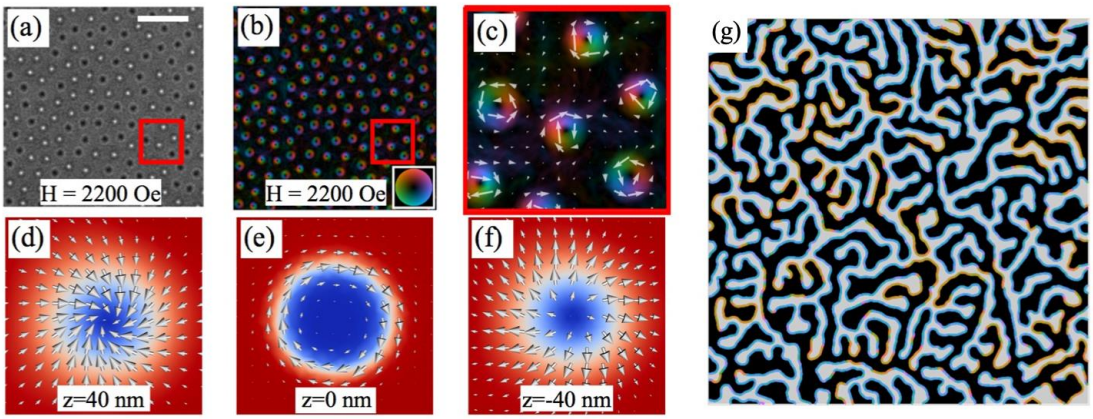

Figure 1: (a) Under-focused Lorentz TEM image of a field-stabilized skyrmion lattice in [Fe/Gd]x80 multilayer at room-temperature. (b-c) Images detail the magnetic induction colormaps of (a). (d-f) Micromagnetic modeling of the depth-dependent spin structure of a skyrmion along the top (z = 40nm), center (z = 0nm), and bottom (z = -40nm) surfaces. (g) Postprocessed Lorentz TEM image depicting the remanent domain morphology of an [Fe/Gd/Fe/Ir/Pt]x80 multilayer at T = 160K. Right-chiral Bloch-lines appear as blue-hue lines and left-chiral Bloch-lines are shown as orange-hue lines, while the positive/negative perpendicular magnetization is depicted as gray/black features.

Nanolasers: Dynamics and Phase Locking

Shaya Fainman

We discuss nanoscale metal-dielectric-semiconductor resonant gain geometries to create a new type of light emitters focusing on three key aspects: second order intensity correlation characterizations, direct modulation and coupled nanolasers dynamics.

Short Bio:
Yeshaiahu (Shaya) Fainman is Cymer Chair and Distinguished Professor in Electrical and Computer Engineering (ECE) at the University of California, San Diego (UCSD). He received the Ph. D. from Technion-Israel Institute of Technology in 1983. He is directing research of the Ultrafast and Nanoscale Optics group at UCSD and made significant contributions to near field optical phenomena, inhomogeneous and meta-materials, nanophotonics and plasmonics, and non-conventional imaging. His current research interests are in near field optical science and technology with applications targetting information technologies and biomedical sensing . He contributed over 320 manuscripts in peer review journals and over 540 conference presentations and conference proceedings. He is a Fellow of the OSA, IEEE, SPIE, and a recipient of the Miriam and Aharon Gutvirt Prize, Lady Davis Fellowship, Brown Award, SPIE Gabor Award, OSA Emmett N. Leith Medal, OSA Joseph Fraunhofer Award/Robert M. Burley Prize and Nick Holonyak Jr Award, OPTICA (former OSA).

Coherent coupling to a thicket of spin-wave modes in an ultrastrongly coupled microwave-magnon system

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A major challenge for quantum technology is the integration of low-damping and low saturation magnetic materials with planar superconducting circuits. This would allow for isolation of microwave signals, as well as provide a medium for nonlinear electromagnetic phenomena such as microwave to optical quantum transduction. Here we will describe a novel material, vanadium tetracyanoethylene ($V[TCNE]_x$), which has ultra-low intrinsic damping, can be grown at low temperatures on arbitrary substrates, and can be patterned on the nanoscale while retaining its low-loss properties. In recent work [1] a thin-film superconducting resonator was coupled to a low-damping, thin-film, $V[TCNE]_x$ microstructure, achieving a cooperativity > 10^3 and entering the ultrastrong coupling regime.

The resonator-magnon system in Ref. 1 exhibits fine structure showing multiple magnon modes. The nature, frequency, and coupling strength of these modes appears to depend on the detailed shape of the magnonic material. The resonator, therefore, provides a very low loss “bus” coherently connecting these spin waves together, offering the potential for coherent information processing wherein the information is encoded in spin wave excitations.

The theory of uniform magnon coupling was supported through the Center for Molecular Quantum Transduction (CMQT), an Energy Frontier Research Center supported by the Department of Energy Office of Science, Basic Energy Sciences (DE-SC0021314), and the theoretical analysis of finite-k magnon modes was supported by the Department of Energy Office of Science, Basic Energy Sciences (DE-SC0019250).

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How to turn charge into spin

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Spin and charge degrees of freedom are coupled to each other via spin-orbit coupling. This allows to convert charge currents into spin currents, which thereafter can be used to manipulate magnetizations; a concept that is now known as spin-orbitronics. Charge-to-spin current conversion in the bulk are called spin Hall effects. Very early non-local measurements in gold created a puzzle with very disparate magnitudes of spin Hall effects were measured [1,2]. This puzzle was resolved later as being due to the thickness, when we discovered that spin Hall effects can be significantly enhanced when the thickness of gold films is reduced [3]. In addition, we investigated how reduced symmetries can give rise to spin Hall effects with directions of spin polarizations that are ordinarily prohibited. Of particular interest are metallic antiferromagnets, since the antiferromagnetic structures may reduce the symmetry beyond the symmetries of the crystal lattice giving rise to magnetic spin Hall effects [4]. Furthermore, we discovered that FeRh can generate in its antiferromagnetic state unconventional spin Hall effects with very large charge-to-spin conversion efficiencies [5].

This work was supported as part of Quantum Materials for Energy Efficient Neuromorphic Computing (Q-MEEN-C), an Energy Frontier Research Center funded by the US Department of Energy, Office of Science, Basic Energy Sciences under Award No. DE-SC0019273.

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Shaken, not stirred: a recipe for magnetic switching via phononic resonances

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Strong light-matter interaction constitutes the bedrock of all photonic applications, empowering material elements to create and mediate interactions of light with light. Among others, phonon-amplified interactions were shown to bring a specific twist into this, in the infrared (IR) frequency range. Thus, phono-magnetic effects are the low-frequency analogues of inverse Faraday and Cotton-Mouton effects [1,2] where phonons, not electrons, mediate the interaction between light and spins. In this case, light couples to the spins indirectly by exciting coherent vibrations of the crystal lattice (phonons) that transfer angular momentum to the magnetic ions [3,4]. The optically driven chiral phonons in materials with strong spin-orbit coupling were shown to produce giant effective magnetic fields that exceed those previously seen by several orders of magnitude [5]. The mechanism allows for bidirectional control of the induced magnetization through phonon chirality that in turn can be controlled by the polarization of the laser pulse.

Here we show that through the resonant excitation of circularly-polarized optical phonons in paramagnetic substrates, one can permanently reverse the magnetic state of the substrate-mounted heterostructure [6]. With the handedness of the phonons steering the direction of magnetic switching, such effect offers a selective and potentially universal method for exercising ultrafast non-local control over magnetic order.

Moreover, a different behaviour, characterized by displacive modification of magnetic potentials, can be observed when exciting materials at phonon frequencies with linearly-polarized light. The magnetic switching was shown to create very peculiar patterns [7], confirming the mechanism, but also creating novel dynamic phenomena such as self-organization of magnon-polarons [8].

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Saturday September 2nd

9:00 – 9:25
Magneto-Ionic Control of Spin Textures and Interfaces
Kai Liu
9:25 – 9:50
Using magnetism to act on living cells
Bernard Dieny
9:50 – 10:15
World Materials Forum
Victoire de Margerie
Coffee break: 20 minutes
10:30 – 10:55
Recent advances in spin Hall nano-oscillators: 10 nm devices and mutual synchronization of 1000s of oscillators
Johan Akerman
10:55 – 11:20
Local probing of electric field-induced manipulation of magnetization
Kristiaan Temst
11:20 - 11:45

Ray Osborn
11:45 – 12:10
Enhancing domain wall motion in W-CoFeB-MgO materials using He+ ion irradiation
Dafiné Ravélosona
12:10 AM - 2:00 PM: lunch & posters
2:00 - 2:25
Towards on-chip spintronic-photonic integration
Bert Koopmans
2:25 - 2:50
Tunable coupling in magnetic thin film heterostructures with a magnetic phase transition
Casey Miller
2:50 - 3:15
Tuning magnetic phase transitions in thin films and multilayers
Andreas Berger
3:15 - 3:40
From Spin Transfer Torque (STT) to all optical STT
Stéphane Mangin

Magneto-ionics with alternative ionic species

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Magneto-ionic (MI) effects have shown promise for energy-efficient nanoelectronics, where ionic migration can be used to achieve atomic scale control of interfaces in magnetic nanostructures, and in turn modulate a wide variety of functionalities. To date, magneto-ionics have been mostly explored in oxygen-based systems, while there is a surge of interest in alternative ionic systems [1]. We have recently demonstrated effective MI control using a variety of ions. In hydrogen based systems, we have found a sensitive and reversible chirality switching of magnetic domain walls [2] and writing/deleting of skyrmions [3] via hydrogen chemisorption/desorption. In hydroxide based α-Co(OH)2 films, a reversible paramagnetic to ferromagnetic transition is observed after electrolyte gating with a low turn-on voltage [4]. In nitride based Ta/CoFe/MnN/Ta films, chemically induced MI effect is combined with the electric field driving of nitrogen to effectively manipulate exchange bias (Figs. 1a-1b) [5]. These effects offer an ideal platform to gain quantitative understanding of magneto-ionics at buried interfaces, leading to electric modulation of magnetic functionalities. They are also relevant for 3-dimensional information storage as a potentially contactless way to address spin textures, such as in interconnected magnetic nanowire networks (Fig. 1c) [6].

This work has been supported in part by the NSF (ECCS-1933527, ECCS-2151809, DMR-2005108), SRC/NIST, and KAUST.

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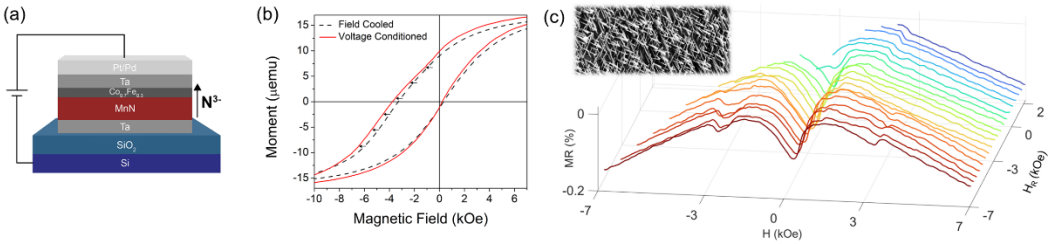

Figure 1: (a) Schematic illustration and (b) the corresponding exchange bias effect that is electrically enhanced in a Ta (10 nm)/MnN (30 nm)/CoFe (1 nm)/Ta (10 nm)/Pd (10 nm) thin film sample at 10 K. (c) First-order reversal curve measurements of magnetoresistance of interconnected Co nanowire networks (inset).

Using magnetism to act on living cells

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The mechanical vibration of magnetic particles (Fig.1) under low frequency magnetic field allows applying mechanical stress at the cell level. The magnetic particles are designed to have superparamagnetic-like properties to avoid agglomeration [1] and sufficiently large volume to exert forces in the pN range to produce significant mechanobiological reactions on cells. This mechanical stress induces a large variety of physiological reactions from the cells depending on the nature of the cells and on the intensity of the magneto-mechanical stimulation. A great advantage of using magnetism in this field of mechanobiology is that the induced stress can be easily tuned remotely by playing on a number of parameters such as external magnetic field amplitude, direction, frequency. The mechanical stress has a strong influence on the cells cytoskeleton which triggers a variety of signalling pathways and consequently, of physiological reactions.

Using U87 glioma brain cancer cells, we observed that a weak stimulation induces already a disorganization of the cell cytoskeleton (Fig.2) resulting in a cell contraction, a loss of motility (ability of the cell to migrate) and a stop of the mitosis (stop of proliferation). A stronger stimulation can induce the apoptosis (spontaneous death) of the cells (Fig.3) [2-4]. Thanks to a stimulation with a moderate alternating field of 20mT at 20Hz for 30minutes, the death of 80% of the cancer cells can be induced, in particular via apoptosis. Remarkably, the still alive cells do not proliferate any more during several days. The magneto-mechanical treatment can be repeated until the cancer cells are fully destroyed. This approach can lead to a new approach towards cancer treatment, used alone or in conjunction with chemotherapy. An even stronger stimulation can result in a disruption of the cell membrane and thereby cell necrosis, which is not desirable because it goes with inflammatory reactions and may cause metastasis.
Studies on cancer cells were conducted *in-vitro* as well as *in-vivo* revealing quite different results for a variety of reasons. Ongoing studies are carried out on spheroids of cells embedded in 3D gels which represent *in-vitro* models much closer to *in-vivo* situations.

Experiments were also conducted on pancreatic cells [5]. We demonstrated that the magnetically induced mechanical stimulation of pancreatic cells allows enhancing insulin secretion from INS1 pancreatic cells (Fig.4). The experiments were conducted both by culturing pancreatic cells on vibrating magnetic membranes as well as by dispersing vibrating magnetic particles among the pancreatic cells. This observation can also open a new route towards innovative diabetes 2 treatments [3] whereby the insulin level of a diabetic patient would be increased not by injection of insulin with a syringe but by an external magnetic field with magnetic particles being permanently dispersed in the pancreas.

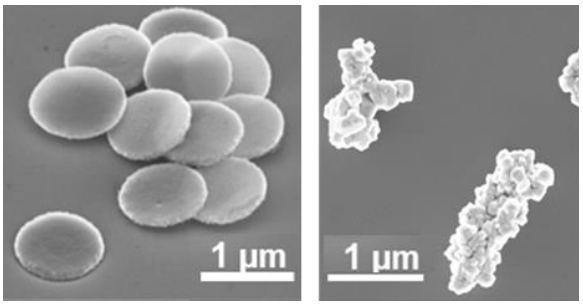

Fig. 1: Two types of superparamagnetic-like particles used for the magneto-mechanical stimulation of cells : Magnetic Au coated NiFe vortex nanoparticle (left) and magnetite nanopowder (right).

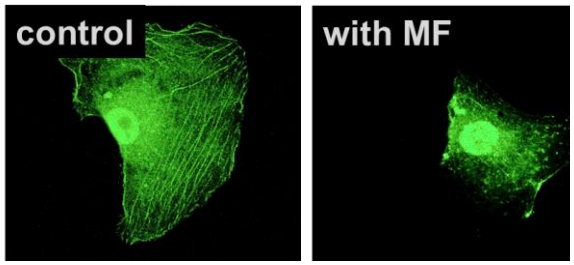

Fig. 2. U87 cancer control cell with stained actin cytoskeleton (left). Cell with damaged cytoskeleton after NP magneto-mechanical vibration (right).

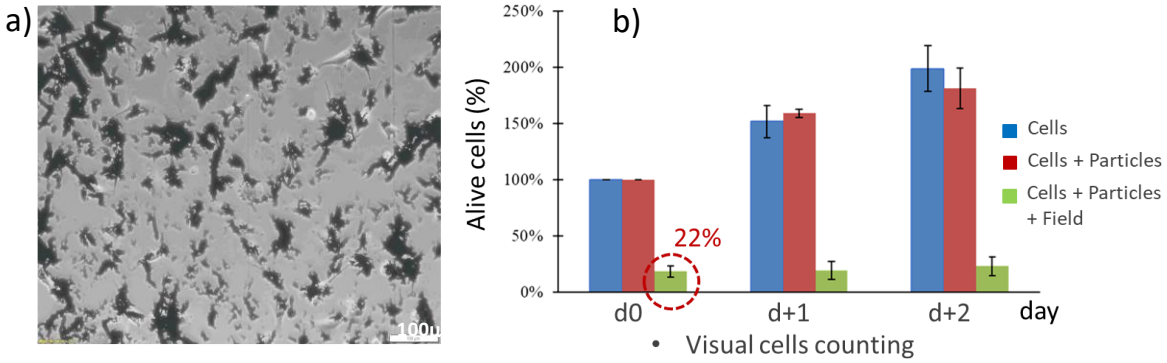

Fig.3: a) Glioma cancer cells incubated with NiFe vortex microdisks. Interestingly, the cells catch all magnetic particles even without functionalization. b) In vitro testing of magneto-mechanical stimulation of glioma cells. Blue and red bars correspond to controls (cells without particles and cells with particles but no oscillating field), green bar: Cells with particles submitted to oscillating field (20mT, 20Hz). ~80% of the cancer cells die after treatment. Interestingly, the still alive ones do not proliferate during several days.

The World Materials Forum

Victoire de Margerie

ICoChair of the World Material Forum – Nancy – France

The World Materials Forum (WMF) is an international conference dedicated to fostering collaboration and accelerating the implementation of sustainable materials solutions that make it possible to decouple economic growth from the use of our natural resources, while meeting the needs of our citizen and creating value for our industries. We emphasize the vital role of fast-scaling research to bridge the gap between groundbreaking ideas and real-industry applications, recognizing the urgency of the situation. And we expect this fast scaling from gathering in person at the forum 300 + industry leaders, top league researchers, global policymakers and breakthrough entrepreneurs.

The World Materials Forum takes place every year in June or early July in Nancy – France and feature keynote speeches, panel discussions, start up awards and networking opportunities.

Figure 1: Philippe Varin and Prof. Victoire de Margerie with the Global Battery Community at WMF 2023.

Eric Fullerton is a friend of the world Materials Forum. In 2022 he was a speaker for a second time and animated a scientific debate with Luc Julia (Chief Scientific Officer – Renault) on the impact of Electronics.

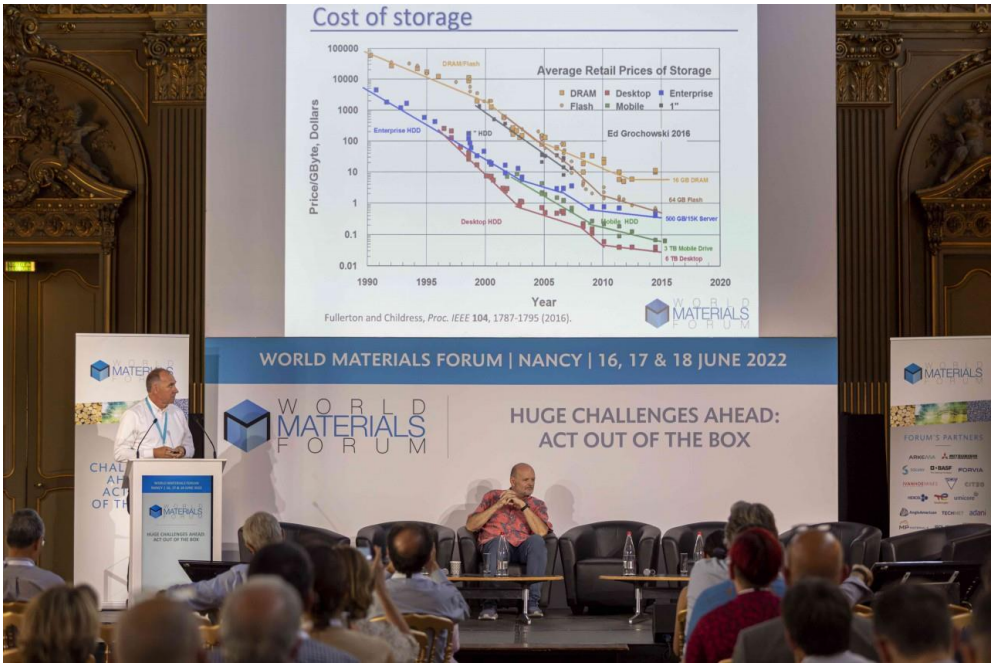

Figure 2: Professor Eric Fullerton at WMF 2022

Progress towards 10 nm spin Hall nano-oscillators and mutual synchronization of thousands of oscillators

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Mutually synchronized spin torque nano-oscillators (STNOs) are one of the promising platforms for bioinspired computing for tasks such as vowel recognition [1]. Recently, mutual synchronization [2] of spin Hall nano-oscillators (SHNOs) was used for the same task [3]. However, the number of mutually synchronized SHNOs remains limited: up to 50 in the most recent chains [4] and 64 in 2D arrays [3]. To synchronize much larger arrays, one must increase the mutual interaction strength between oscillators. One way of increasing the coupling strength is to make the oscillators more closely packed, and the first important step is to make all nano-constrictions in a 2D SHNO array much smaller.

Here, we present a detailed experimental study on how to shrink the width of nano-constriction SHNOs. We show that at extreme miniaturization, current shunting through the Si substrate becomes a problem and results in poor scaling below 50 nm. We, therefore, investigate the use of different seed layers and find that an ultra-thin (3 nm) AlOx layer between the Si substrate and the W layer in W/CoFeB/MgO-based SHNOs, provides a dramatic improvement. As a result, we demonstrate 10 nm SHNOs operating at threshold currents as low as 30 uA [5]. We finally fabricate very large SHNO arrays based on this optimized stack and find that we can synchronize thousands of SHNOs.

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Local probing of electric field-induced manipulation of magnetization

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In multiferroic materials, the coupling between ferroic order parameters like ferromagnetism (FM) and ferroelectricity (FE) (called magnetoelectric (ME) coupling) attracts significant attention. In our work we couple the FM and FE materials via an interface in a multilayer structure with the aim of studying in detail the magnetic spin structure at the interface. We have studied the evolution of the interface of Fe/(LNO, BTO) systems as function of the applied electric field using the isotope sensitivity of Mössbauer spectroscopy and nuclear resonant scattering (NRS) of synchrotron radiation on samples with a 1 nm ^{57}Fe probe layer at the interface. The results show the formation of a thin magnetically dead layer at the interface between the metal and the FE oxide due to ion transport across the interface. Based on our results we propose a model [1] for the effect of an electric field on the metal/FE oxide interface and validated it with Mössbauer spectroscopy results. During the growth of a metal on top of a FE oxide, electron transport occurs across the interface due to the work function difference between the metal and the oxide (with high dielectric constant), which leads to the formation of a built-in electric field at the interface. Depending on the direction of the built-in field, the direction of the applied electric field either favors the ion transport across the interface or opposes it until the external field overcomes the built-in field (after applying electric field above a critical value). With recent NRS results, we have identified the values of the critical field for both Fe/BTO and Fe/LNO systems. These findings are not only applicable to Fe/(LNO,BTO) interfaces but also improve the understanding of metal/FE oxide interfaces in general.

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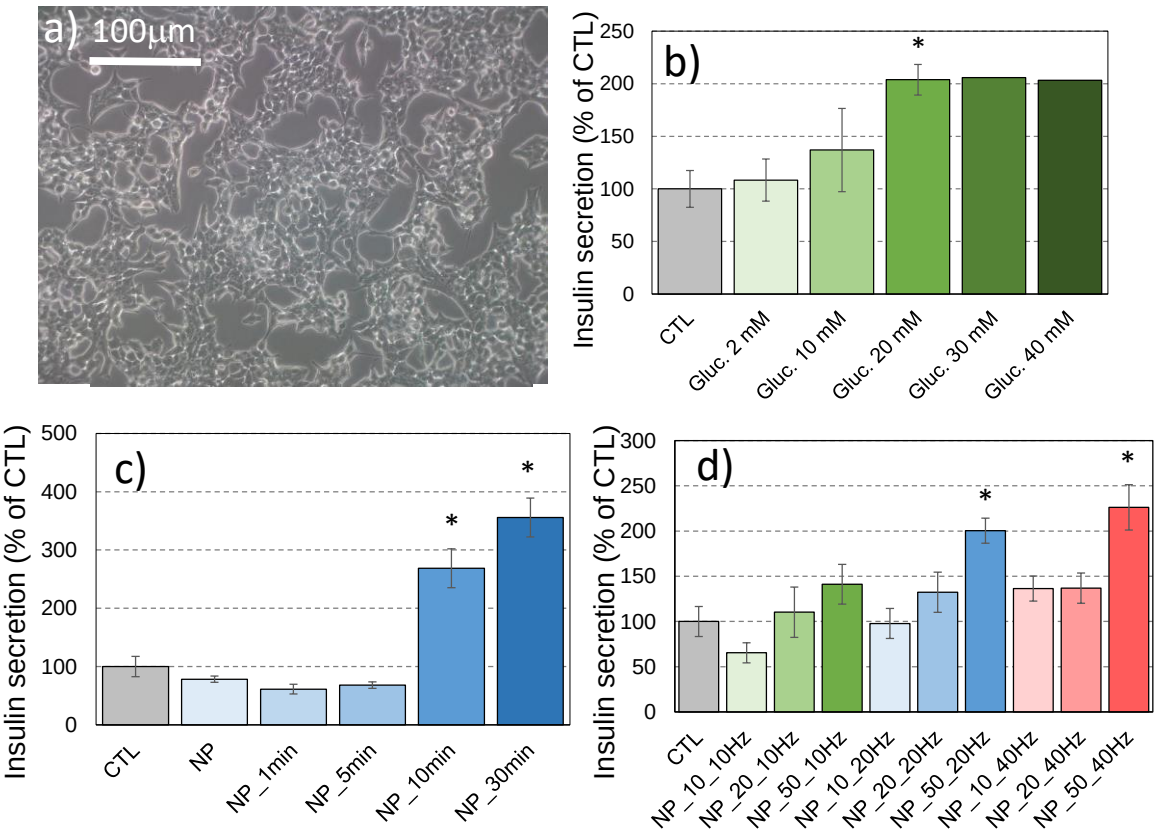

Fig.4: a) INS1 pancreatic cells: b) Insulin production when the pancreatic cells are exposed to increasing glucose content (CTL=control=INS1 cells without glucose exposition); c) Insulin production under magnetically induced mechanical stimulation of the cells. It clearly appears that for stimulation longer than 10 minutes, a very pronounced increase in insulin secretion is observed; d) Influence of filed amplitude (10, 20, 50mT) and frequency of oscillating field (10, 20, 40Hz) on insulin secretion.

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Enhancing domain wall motion in W-CoFeB-MgO materials using He^+ ion irradiation

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Spintronic devices based on domain wall (DW) motion offer new exciting opportunities for non-volatile data storage, neuromorphic, and logic applications. Pinning of DWs due to structural disorder limits the efficiency of DW motion based devices. Such disorder in materials and devices usually takes the form of spatial variation of magnetic properties due to interface roughness, intermixing, crystalline texture or grain boundaries as well as edge defects induced by nanofabrication processes. He^+ irradiation is a powerful tool to engineer magnetic materials at the atomic scale enabling the control of magnetic properties [1]. The utilization of light ions provides the precise control of inter-atomic displacements through low energy transfer. In this work, we use He ion irradiation to reduce domain wall pinning in W-CoFeB-MgO systems with perpendicular anisotropy by (i) enhancing the crystallization process [2] and (ii) locally tuning the edges of micro sized wires. We have studied domain wall motion in W/CoFeB/MgO thin films with perpendicular magnetic anisotropy crystallized by annealing at 400◦C and a process based on He+ irradiation combined with moderated temperatures. We show that despite similar magnetic properties (effective anisotropy, magnetization, Gilbert damping, Dzyaloshinskii-Moriya interaction) for the whole series of samples, domain wall mobility is critically improved in the irradiated samples. This is due to a smoother pinning potential with a narrower distribution of energy barriers for samples crystallized through ion irradiation. Finally, we have locally irradiated the edges of W-CoFeB-MgO wires, with widths between 5 µm and 40 µm. We demonstrate that the edge pinning can be quenched resulting in a significant increase in the DW velocity in the narrower wires.

In summary, the possibility to reduce structural defects through He ion irradiation paves the way toward power-efficient memory and neuromorphic devices.

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Towards photonic-spintronic integration

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In the spirit -and honor- of Eric Fullerton, this presentation will address the opportunities for the integration of spintronics with photonics (Figure 1). Novel schemes for controlling the ferromagnetic state at femtosecond time scales by pulsed laser excitation have received great interest. By driving systems into the strongly non-equilibrium regime, it has been shown possible not only to quench magnetic order, but also to switch the magnetization by single laser pulses – so-called all-optical switching (AOS). In parallel, it has been found that pulsed laser excitation can also induce spin currents over several to tens of nanometers, which can act as an additional source of sub-picosecond magnetization dynamics. Thereby, a scientifically exciting link between the fields of 'femtomagnetism' and spintronic transport physics has emerged. Moreover, it is being envisioned that combining the two fields could pave the way to a new class of hybrid spintronic-photonic devices, in which data is copied between photonic and magnetic (spintronic) domain without any intermediate electronic steps, leading to ultrafast and highly energy-efficient IT solutions.

In this presentation, some of the underlying phenomena will be addressed, and recent progress on scientific issues that are considered key for realizing the envisioned technology will be discussed. Examples of progress towards integrated spintronic-photonic devices will be presented, including current-induced domain wall motion in Pt/Co/Gd-based conduits that display efficient AOS [1] with domain-wall velocities over 2000 m/s [2], AOS of MTJs [3], as well as on-chip magneto-optical reading of 300 x 400 nm2 magnetic elements structured on top of InP photonic waveguides [4]. Finally, to further reduce the device footprint and increase data densities, near-field plasmonic approaches will be in inevitable. Recent device simulations on using photonic cavities and plasmonic nano-antennas for sub-diffraction limited optical writing and reading [5] provide inside into pushing the ultimate performance.

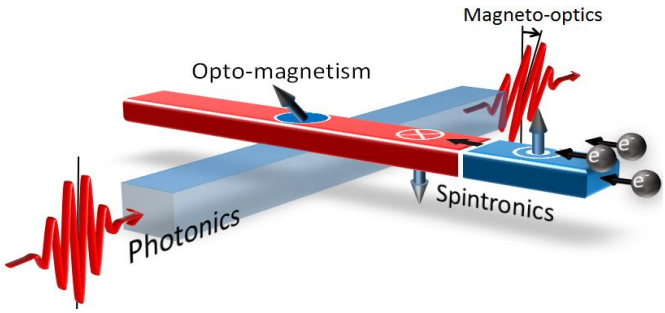

Figure 1: Schematic representation of photonic-spintronic integration.

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Tunable coupling in magnetic thin film heterostructures with a magnetic phase transition

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The magnetic properties of permalloy-based trilayers of the form Py0.8Cu0.2/Py0.4Cu0.6/Py/IrMn were studied as the spacer layer undergoes a paramagnetic to ferromagnetic phase transition [1]. We find the coupling between the free Py0.8Cu0.2 layer and the exchange bias pinned Py to be strongly temperature-dependent: there is negligible coupling above the Curie temperature of the Py0.4Cu0.6 spacer layer, strong ferromagnetic coupling below that temperature, and a tunable coupling between these extremes. Polarized neutron reflectometry was used to measure the depth profile of the magnetic order in the system, allowing us to correlate the order parameter with the coupling strength. The thickness dependence shows that these are interface effects with an inverse relationship to thickness, and that there is a magnetic proximity effect that enhances the Curie temperature of the spacer layer with characteristic length scale of about 7 nm. As a demonstration of potential functionality of such a system, the structure is shown to spontaneously flip from the antiparallel to parallel magnetic configuration once the spacer layer has developed long-range magnetic order.

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Tuning magnetic phase transitions in thin films and multilayers

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In the field of magnetism, phase transitions play a very important role for scientific, historical and practical reasons. On one side, the ferromagnetic-paramagnetic phase transition is a prime example of a 2nd order phase transition and associated critical behavior and the same is true for magnetization reversal and 1st order phase transitions. As such, the field of magnetism has contributed and still contributes to the scientific analysis of phase space behavior of macroscopic system and the understanding of thermodynamic properties [1]. In a similar way, magnetic systems are also relevant in developing a quantitatively accurate understanding of non-equilibrium physics and dynamic phase transitions, for instance [2]. On the other hand, phase transitions are a core ingredient of the utility of magnetic materials in many applications, both for existing mass market technologies as well as for emerging novel applications. A prime example of the former is the utilization of the bi-stability that is associated with ferromagnetic hysteresis in the vicinity of the phase boundary for the purpose of non-volatile data storage, such as in HDDs, tape storage, MRAM and more recent device concepts that combine magnetic information storage and processing [3,4]. In all cases, the operational quality of these devices is reliant on the precise tunability of materials properties, in particular the exact shape and dimensions of the ferromagnetic hysteresis loop, its speed and temperature dependence, in addition to other relevant materials properties. On the opposite end of the application spectrum as far as the hysteresis properties of ferromagnetic materials are concerned are transformer and electro-motor and -generator components, where the steep change of magnetization with magnetic field near the 1st order phase transition is being utilized. For these applications it is crucially important to suppress the occurrence of hysteresis to avoid relevant energy losses in operation, and associated material designs and developments are targeted towards this goal. Examples of utilizing the 2nd order ferromagnetic phase transition include magnetic refrigeration, hypothermia cancer treatments as well as data applications that use thermally assisted processes [3,4].

Phase transitions have played a similar role in the field of magnetic thin films and multilayers, because on one side, certain technologies such as data storage evolved in the direction of thin films, and thus magnetic thin film properties and phase transitions had to be explored and associated materials science was developed. On the other side, key fundamental aspects of magnetic phase transitions could be explored, such as for instance the transition from 3-dimensional to 2-dimensional behavior, which was predicted to behave very differently and suggested to be incompatible with long-range ferromagnetic order for certain lattice symmetries. So, very substantial efforts were dedicated to exploring phase transitions in thin films and multilayers [5].

Due to the finite thickness of thin magnetic films and the associated very specific geometric shape of a laterally extended, thin plane, other phase transitions could also be explored. One such example is the reorientation phase transition, that can lead to rather anomalous effects and temperature evolutions of magnetic properties due to the very distinct competition of different energy contributions, specifically magnetic anisotropy and magnetostatic energy, making it frequently possible to precisely predict domain phases and pattern that are generally not feasible in bulk ferromagnets [6,7]. Also, surface induced phase transition, such as the surface spin-flop phase transition are possible and observable in thin film geometries, aiding the qualitative and quantitative understanding of magnetic phase transitions by exploring them in thin films and multilayers [8].

Besides the dimensionality, finite thickness and shape aspects, other aspects can also alter and modify the occurrence and evolution of phase transitions in thin films. This can occur in terms of rather

local electronic state modifications of moment strength, exchange coupling, or anisotropy, which generally leads to a shift of the energy minimum and associated phase diagram, such as for instance by enhancing perpendicular magnetic anisotropy in Co/Pt or Co/Pd multilayers [9]. However, also more fundamental modifications of magnetic phase diagrams can occur, as for instance, by mediating interlayer exchange coupling through non-magnetic interlayers, which breaks the independence of individual layers and thus leads to an enhanced complexity of the collective magnetic multilayer systems [9]. This also occurs, when different layers in a multilayer stack have different order parameters, that are not necessarily compatible at the interface. This can lead to a multitude of phases for the combined system such as for instance in Fe/Cr bi- and multilayers [10,11].

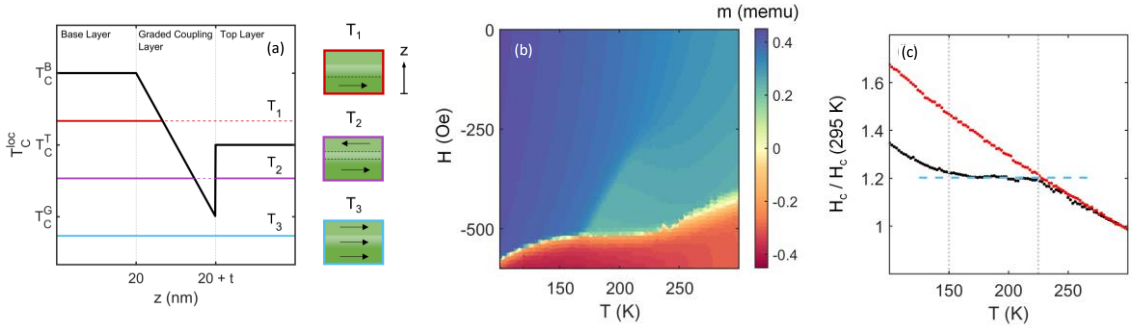

Figure 1: (a) schematic of T_C^{loc} as a function of depth z in a multilayer sequence composed of a base layer with high T_C^B, a top layer with intermediate T_C^T and a coupling layer with an exchange graded profile. The solid portions of the horizontal-colored lines represent the regions of the film, in which a FM state can be expected for three different temperatures T_1, T_2, and T_3, while the dashed lines symbolize presumed PM regions. On the right-hand side, schematics of the FM magnetization profiles are displayed for the three highlighted temperatures. The green color grade represents the local exchange energy, and the black-dashed lines represent the expected PM/FM interfaces. The arrows represent the portion of the film exhibiting a FM state; (b) color-coded map of the experimentally measured total sample magnetization as a function of T and H for a multilayer sample containing an exchange graded layer with t = 20 nm. The data are obtained for decreasing field sequences, each for a fixed T value. The color bar on the right-hand side represents the values of total moment; (c) experimental H_c vs. T data normalized to their room temperature value for the t = 20 nm multilayer sample (black) and a reference film sample without top layer (red). The grey-dashed vertical lines represent the temperature range, in which two separate FM entities coexist and the light blue dashed horizontal line represents the constant coercivity in this specific temperature range [14].

While such novel phases and their exploration and classification are fundamentally very interesting, much of the materials related work has been focused on tuning specific magnetic quantities for application purpose by utilizing available fabrication capabilities of magnetic multilayers. One such example is the exchange spring recording media approach, in which a depth-dependent anisotropy strength enables high magnetic stability in conjunction with sufficiently low coercive fields, a technological achievement that enabled most substantial advances in HDD recording densities [12]. An alternate approach was the introduction of exchange graded magnetic multilayers and films, which have a distinct depth dependence of the exchange coupling strength. While the basic concept of this approach was known for years, recent work demonstrated that it is possible to fabricate magnetically anisotropic films, whose coercivity is essentially zero for a substantial temperature range below the Curie temperature due to the massively enhanced susceptibility of the sample portion that is near its local Curie-temperature [13]. More complex designs of exchange graded materials even allow for the design of wide temperature ranges, in which the coercive field plateaus as shown in Fig. 1, even if the constituting films and materials by themselves have very conventional temperature evolutions of magnetic properties, including a strongly decreasing coercive field with increasing temperature [14].

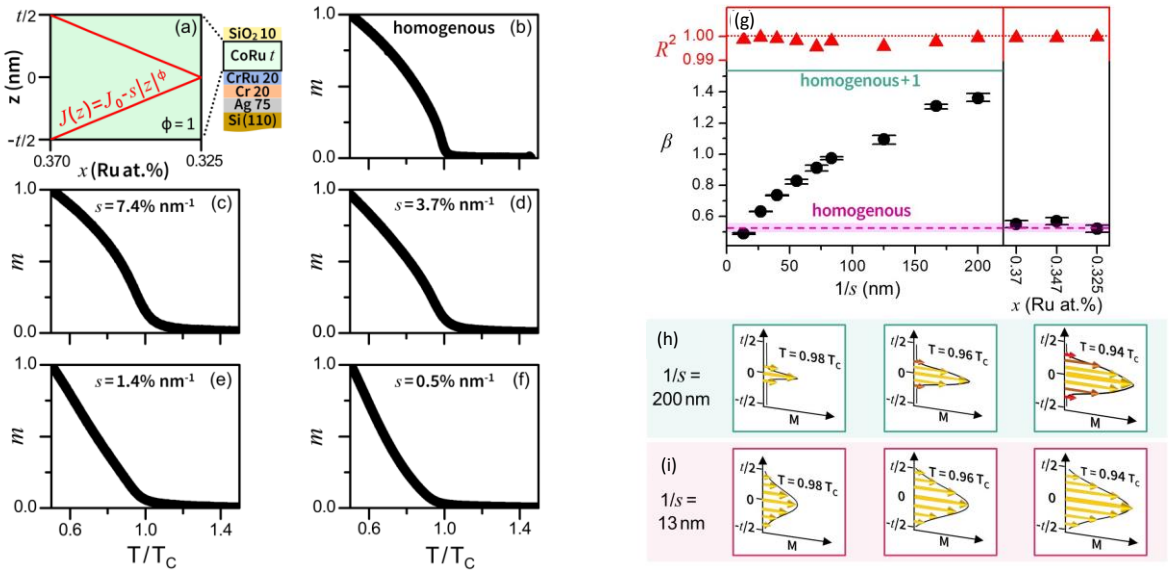

Figure 2: (a) Depth profile of Ru content for CoRu graded alloy films, which is part of an overall layer growth sequence to facilitate epitaxy (layer thickness in nm); (b) – (f) temperature dependence of the normalized easy-axis magnetization $m = M/M(T/T_C = 0.5)$ for a $Co_{0.675}Ru_{0.325}$ homogenous film (b), and graded structures for s = 7.4% (c), 3.7% (d), 1.4% (e), and 0.5% nm^{-1} (f). The data were measured while cooling each sample from T = 300 K to T = 50 K in the presence of an applied field $\mu_0 H$ = 4 mT; (g) $1/s$ dependence of the extracted critical exponent β (black circles) together with the confidence interval of each least-squares fit, and the corresponding R^2 coefficients (red triangles). The red line displays R^2 = 1. The pink dashed line indicates the average measured β value for the homogenous systems investigated for comparison, shown on the right side of (g), while the straight green line indicates this value + 1. (h) and (i) show schematics of the temperature evolution of the magnetization depth profile for a system with $1/s$ = 200 nm and 13 nm, respectively [15].

Recently, such exchange graded materials have also been demonstrated to allow for a very broad manipulation of critical behavior near the Curie temperature, including an extremely large modification of the magnetic onset critical exponent β, which like all other critical properties was understood to be universal and thus not tunable by any kind of materials design. However, this universality can indeed be circumvented by a materials geometry that makes the magnetic film system a mixed dimensionality entity, which is neither 2 nor 3 dimensional as demonstrated in Fig. 2 [15]. This is obviously of fundamental relevance, but can also have significance in terms of applications that have to do with the onset of ferromagnetism, such as thermally assisted processes, given that it opens up additional design options for materials engineering.

Phase transitions in magnetic films and multilayers have been crucial for many scientific and technological developments for many years. Recent work and advances demonstrate that this very successful scientific and technological journey is by no means at its end. Instead, it can be expected that the symbiosis of thermodynamic and dynamic phase transition work with the development of novel thin film and multilayer material concepts will keep producing significant progress and relevant scientific advances in the future.

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From Spin Transfer Torque (STT) to all optical STT

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Over the past two decades, I have been fortunate to have Eric Fullerton as a mentor, manager, colleague, collaborator, and, most importantly, as a friend.
In August 2004, Eric Fullerton became my manager during my one-year tenure as an invited scientist at the Almaden Research Center in San Jose. It was under his guidance that we developed a groundbreaking approach to growing [Co/Ni] as a Perpendicular Magnetic Anisotropy (PMA) material. Through this innovation, we successfully demonstrated current-induced switching in PMA spin-valve structures [1], as well as current-induced domain wall motion in PMA films [2]. These achievements were made possible by the exceptional properties of PMA materials, which allow for efficient current-induced switching via the generation of spin transfer torque (STT).
In collaboration with Andrew Kent's group at NYU, we further investigated the dynamics of STT switching in PMA devices and successfully demonstrated rapid switching in these systems [3].
In August 2012, Eric extended an invitation for me to serve as an invited professor at UC San Diego for one year. This marked the beginning of our exploration into magnetization switching using ultra-short light pulses across a range of magnetic materials [4]. Building upon this work, we advanced our research by generating ultra-short spin current pulses to effectively switch magnetization in various spin-valve structures [5]. Our most recent breakthrough showcases the observable effects of these pulses on magnetization.
Throughout these collaborative endeavors, Eric Fullerton has been an invaluable source of knowledge, guidance, and inspiration. His mentorship has greatly influenced my professional growth and our collective achievements. I am immensely grateful for the privilege of working alongside him and eagerly anticipate future collaborations fueled by his expertise and friendship.

Thank you so much Professor !

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Nature Mat, **114** 36(2023)

POSTERS

Posters:

P1: Alberto Anadon: ***Large Enhancement of Spin-to-Charge Conversion in Fe/Graphene/Pt Interface***

P2: Vladimir Belotelov: ***Unconventional ultrafast spin dynamics in the non-collinear phase of a ferrimagnet***

P3: Jude Compton-Stewart: ***Novel Low-Temperature THz Spectroscopy Setup for Investigating Spintronics THz Emitter Behaviour in Cryogenic and Superconducting Regimes***

P4: Héloïse Damas: ***Spin current generation and self spin-orbit torque in GdFeCo ferrimagnet***

P5: Eva Diaz: ***Spin-orbit torque switching in ferromagnets and ferrimagnets in the picosecond scale***

P6: Niels Fennema: ***Universal switching of magnetization by circularly-polarized phonons***

P7: Anna-Maria Friedel: ***Magnetisation dynamics of epitaxial Co2MnSi Heusler thin films and Co2MnSi/X/Co2MnAl Heusler bilayers for coupling investigations***

P8: Junta Igarashi: ***Laser-induced ultrafast magnetization reversal in STT spin valves***

P9: Henri Jaffres: ***Dynamical spin-charge conversion probed by THz-TDS spectroscopy: from transition metals to ultrathin epitaxial Bi1-xSbx topological insulators***

P10: Lin Jun-Xiao: ***Single Femtosecond laser Pulse Induced In-Plane Magnetization Switching in Ferrimagnetic GdxCo100-x alloys***

P11: Po-Wei Lee: ***Bulk spin-orbit effect in single rare earth-transition metal alloy on the magnetization switching***

P12: Anand Manaparambil: ***Underscreened Kondo cloud in superconductor***

P13: Carmen Martin: ***Layer-resolved Vector Magnetometry using generalized magneto-optical ellipsometry***

P14: Ratthaphong Rang-ngoen: ***Advanced design of mtj for the application of spin torque nano-oscillator***

P15: Ansar Safin: ***Enhancing control of exceptional points through nonlinearity in coupled magnetic oscillators***

P16: Biswajit Sahoo: ***Effect of magnetic ordering on the spin Hall angle of epitaxial Ho(0001) thin films***

P17: Jintao Shuai: ***Separation of heating and magneto-elastic coupling effects in surface acoustic wave-enhanced magnetic domain wall creep motion***

P18: Thanapon Sinkruason: ***The optimal condition of L10/A1 FePt magnetic nanodot for the application in Heated Dot Magnetic Recording technology***

P19: Tobias Sparmann: ***Skyrmion diffusion controlled by alternating current excitations***

P20: Ryunosuke Takahashi: ***Laser-induced magnetization switching in NiCo2O4 thin films***

P21: Artem Talantsev: ***Effects of pattern dimensions on displacement sensitivity of positioning sensors based on magnetic tunnel junction array***

P22: Vojtech Uhlir: ***Phase Coexistence and Ultrafast Dynamics of Magnetic Order in Metamagnetic FeRh Nanostructures***

P23: Yaohan Xu : **Parsing the ultrafast non-local spin transfer in Gd-based Ferrimagnetic spin valves**

Enhancement of spin-charge conversion combining 2D and 3 D materials: towards a new generation of spin-orbitronics devices

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The search for highly efficient systems for the conversion of spin current into charge current is one of the main research activities in today's spintronics. It has been shown that 2D systems with spin-helicity or spin-momentum locking in Rashba states or topological insulators have advantages over their 3D counterparts [1]. Graphene has very weak spin-orbit coupling (SOC) on its own, and thus is a poor converter of spin current into charge current. However, graphene in contact with a high atomic number element such as Au has been shown to strongly increase the SOC [2]. Interestingly, it has also been shown that a significant Dzyaloshinskii–Moriya interaction, and thus a sizable interfacial SOC, appears at the Co/Gr interface [3].

Here we present studies of charge current production by spin pumping. For our study we have grown atomic-thick epitaxial graphene sandwiched between Fe and Pt, Fe/Gr/Pt. As shown in Fig. 1, we see a gain of a factor 20 in charge current production between the Fe/Pt bilayer and our new Fe/Gr/Pt system. Our results show unequivocally the advantage of combining 2D and 3D systems to strongly increase the overall efficiency of spin current and charge current conversion. Consequently, we establish a new route for spin-orbitronic devices.

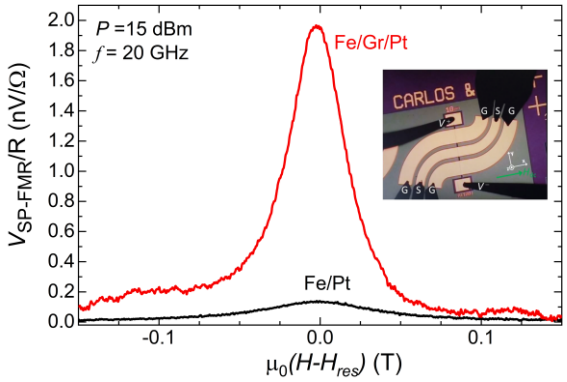

Figure 1: Room temperature raw data of DC spin pumping voltage normalized by slab resistance. We can see a gain of about 20 times in Fe/gr/Pt with respect to Fe/Pt. The inset shows a micrograph of spin pumping device for DC voltage detection. The GSG coplanar wave guide is separated from the slab trough 100 nm of SiO2.

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Unconventional ultrafast spin dynamics in the non-collinear phase of a ferrimagnet

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There are two magnetic phases of the ferrimagnets: collinear and non-collinear ones. Up to now spin dynamics in ferrimagnets has been studied mostly in the collinear state without paying much attention to the kind of the magnetic phase.

We identify an importance of the magnetic phase of a ferrimagnet for its ultrafast spin behavior [1]. A rare-earth iron garnet near magnetization compensation temperature was considered. We demonstrated several crucial peculiarities of spin dynamics in a non-collinear state that contrast sharply with the usually observed spin dynamics of the exchange and ferromagnetic modes in a collinear state far from the compensation point. In particular, when temperature approaches the compensation point the frequencies of quasi-antiferromagnetic (q-AFM) and quasi-ferromagnetic (q-FM) modes behave oppositely: the former decreases, while the latter one grows. The situation changes after crossing the compensation point for higher temperatures. We also discovered that the transition from the non-collinear phase to the collinear one is accompanied with softening of the q-FM mode which leads to a huge increase of the excitation efficiency and amplitude. The amplitude of the soft mode becomes more than 4 times larger than for the collinear state and up to 10 times higher than for the non-collinear phase. As the deflection angle of the soft mode was found to reach ~7°, it can be interesting for all-optical switching and nonlinear magnonics.

The other crucial property of the non-collinear phase is bistability of the Neel vector. It is described by the double well potential energy. If the number of spins in a sample is small enough (~100) then probability of tunneling between two states becomes noticeable and the film will behave in a quantum regime.

Support by the Russian Science Foundation, project N 23-62-10024 is acknowledged.

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A Novel Low-Temperature THz Spectroscopy Setup for Investigating Spintronics THz Emitter Behaviour in Cryogenic and Superconducting Regimes

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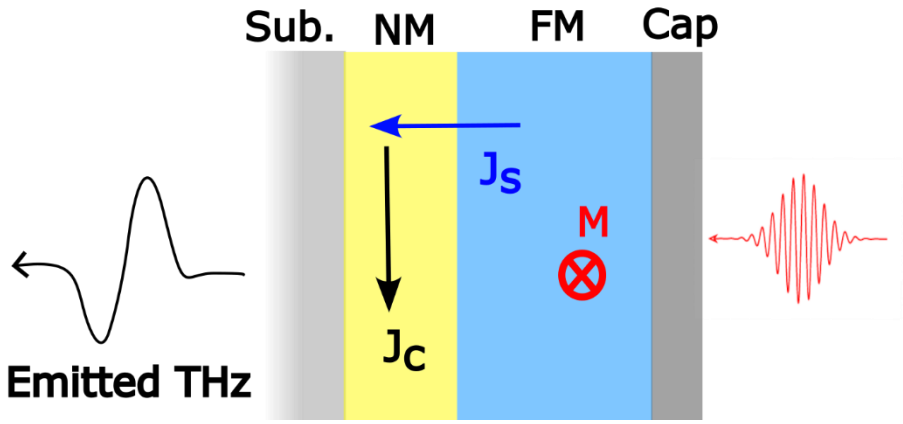
With the emergence of spintronic THz emitters over the last decade, THz spectroscopy has become a powerful tool for investigating spintronic phenomena [1]. When a ferromagnet (FM), coupled to a non-magnetic (NM) heavy metal (typically Pt, Ta or W) is excited by ultrashort laser pulses, the FM layer is rapidly demagnetised. This generates a spin current that upon interaction with the NM layer may undergo a spin-charge conversion via the spin-Hall or inverse Rashba Edelstein effects. The motion of these charges causes the emission of THz frequency radiation, that can then be reconstructed to reveal details of the system's spintronic behaviour. This is outlined below in Figure 1.
Another emerging field of research is that of superconducting (SC) spintronics [2]. In this field, unconventional regimes of SC behaviour are utilised to enhance spintronic behaviour. There exist spin-aligned Cooper pair states, accessible when SC layers are coupled to an inhomogeneous FM interface or are in the presence of spin-orbit coupling. These can carry spin currents substantially larger than those seen in the normal state of the same material [3]. There is also a non-equilibrium regime in which chargeless quasiparticles can be excited above the SC band gap with spin-flip lifetimes orders of magnitude higher than spins in the normal state [4]. These phenomena are promising indicators that superconductivity may be able to significantly enhance certain spintronic behaviours and so we have designed a novel experimental setup for the investigation of cryogenic and superconducting spintronic behaviour via THz spectroscopy, shown below in Figure 2.

Figure 1: Diagram showing the basic mechanism for spintronic THz generation via spin-charge conversion of a



spin current, J_s, incident on a NM layer, most often Pt, Ta or W.

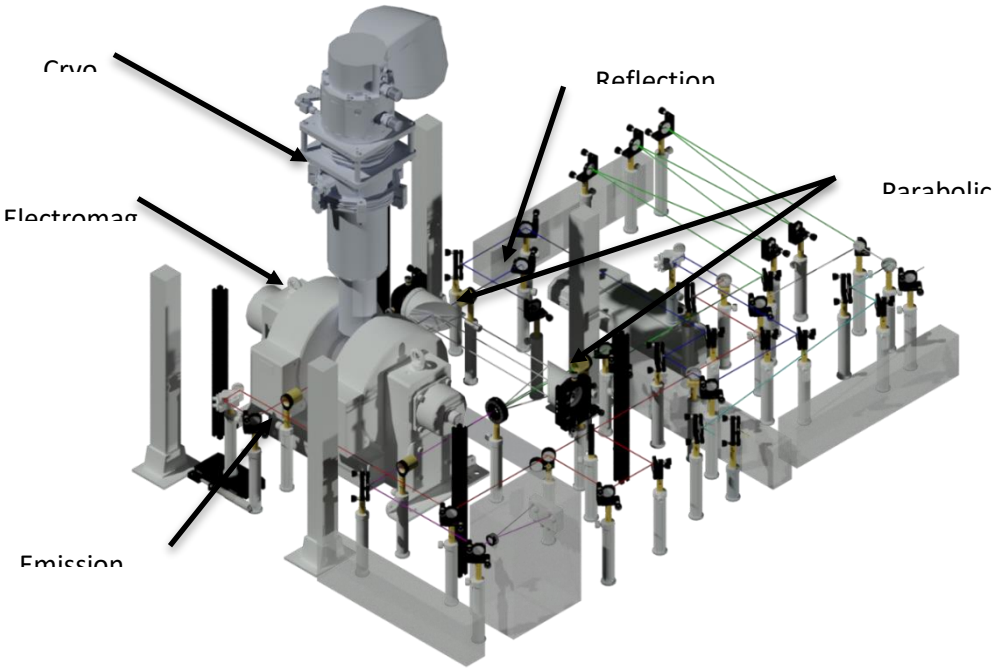


Figure 2: Rendering of a 3D model of the new experimental setup designed to investigate cryogenic and superconducting spintronic phenomena.

This setup uses a cold-finger cryostat as a sample mount placed between the poles of an electromagnet, giving us conditional ranges of roughly 5-350 K in temperature and up to ±1.5 T in in-plane magnetic field. The sample can be excited from either side with THz being collected by the parabolic mirrors, labelled above. This allows for both emission and reflection geometries of THz spectroscopy. We can also access two different double-pump regimes, allowing for spintronic recovery dynamics or double-excitation experiments to be carried out. In one regime, we measure a fixed point of one THz signal while smoothly varying the difference in the pump-pump separation, δt. In the other where we can manually vary δt and characterise a full double-pump THz spectrum. We further plan to include a sample holder capable of electrical transport measurements. These characteristics make this a highly versatile experimental setup, capable of investigating a wide range of material systems, sample geometries, and spintronic phenomena.

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Spin current generation and self spin-orbit torque in GdFeCo ferrimagnet

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Spin-orbit coupling (SOC) enables the interplay between charge, spin and orbital transport, allowing charge-to-spin current conversion in heavy metals (HM) via the spin Hall effect (SHE) [1]. Nowadays, this effect is exploited in spintronics to induce a spin-orbit torque (SOT) on the magnetization of a neighboring magnetic layer [2]. In this work, we present a material that combines the properties of the magnetic layer and SOC: the GdFeCo ferrimagnet, in which the 5d band of Gd induces SOC. GdFeCo is the source of spin currents of different symmetries arising from the spin anomalous Hall effect (SAHE-like spin current) [3,4] and the spin Hall effect (SHE-like spin current) [5,6] respectively. The latter symmetry allows the material to generate a torque on its own magnetization, which we call self-torque [7].

First, we present the study of the spin current generated by GdFeCo and absorbed in a NiFe layer using the ST-FMR technique. From the lineshape analysis in Fig (a), we show that the SHE-like spin current has the same polarization across the magnetization compensation temperature [8]. We then present the study of self-torque performed using harmonic Hall voltage measurements on GdFeCo interfaced with a light metal. We first focus on the temperature dependence of the effective fields associated to the self-torque and show that the effective fields are enhanced near the magnetic compensation temperature and reverse sign above it [7] as depicted in Fig (b).

This study highlights the rich physics of GdFeCo and the potential of rare earth ferrimagnets to be used in spintronics for their SOC.

This work was supported partially from Agence Nationale de la Recherche (France) under contract N° ANR-18-CE24-0008 (MISSION), ANR-19-CE24-0016-01 (TOPTRONICS) and ANR-17-CE24-0025 (TOPSKY), from theFrench PIA project “Lorraine Universite d’Excellence”, reference ANR-15IDEX-04-LUE. D. C.-B., A.Y.A.C and H.D, acknowledge SPIN IJL team for their internship fellow 2018, 2019 and 2020, respectively. DCB also thanks“LUE Graduated” program internship 2019 from “Lorraine Université d’Excellence”.

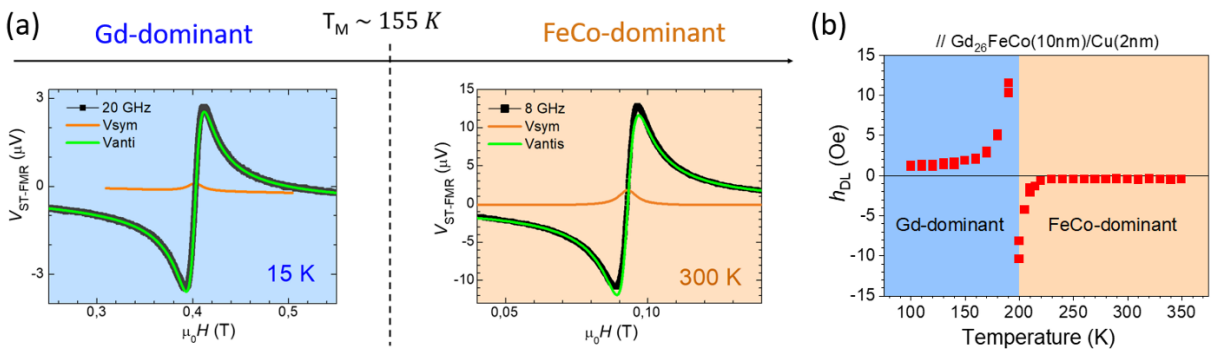

Figure 1: (a) Lineshape analysis at 15K and 300K when the material is Gd-dominant and FeCo-dominant respectively. The symmetric part of the signal (orange fit) is positive for both temperatures, indicating that the polarization of the SHE-like spin current is independent of the magnetic state of the ferrimagnet. (b) Temperature dependence of the damping-like effective field h_{DL} in GdFeCo(10)/Cu(2)/Al(3). Its sign changes through the magnetization compensation temperature represented by the background color change.

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Spin-orbit torque switching in ferromagnets and ferrimagnets in the picosecond scale

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The development of high-speed devices with low energy consumption is currently an important challenge in the memory technology industry. In this regard, spintronic devices, which are based upon the use of the electron's spin degree of freedom, show great potential as an alternative to conventional devices. Within this realm, spin-orbit torque (SOT) switching is a largely studied mechanism which offers desirable qualities, such as high switching speed and energy efficiency. The fastest SOT switching to date has been achieved using a 6 ps electrical pulse over a sample of perpendicularly magnetized Co [1]. The electrical pulse is generated by exciting an Auston switch with a single laser pulse, and is transmitted through a coplanar waveguide (CPW) towards the magnetic sample. By measuring the switching dynamics, it was found that the zero-crossing of magnetization happens in about 70 ps [2]. Moreover, good agreement between data and a macrospin model coupled with ultrafast heating brings forth two important points: (i) the reversal is greatly assisted by Joule heating, which weakens the anisotropy field and thus decreases the energy cost of switching; and (ii) the switching process is coherent, as opposed to the expected domain nucleation and propagation that has been reported for the case of ns pulses [3, 4].

Many aspects of SOT switching remain mysterious in the ps scale. Critical current density, essential for characterizing energy efficiency, has been quantified so far only for pulse durations from the ms scale down to around 200 ps [5]. Regarding materials, SOT switching has been observed in ferromagnets [3–5] and ferrimagnets [6–8] in the ns scale, but the ps scale has, to our knowledge, only been studied in perpendicularly magnetized Co [1, 2].

In this work we show SOT switching of both ferromagnetic and ferrimagnetic materials in the ps scale. We have prepared various samples by magnetron sputtering on a substrate of LT-GaAs. In a similar fashion to Ref. [1], we have developed a sample design including both an Auston switch and a magnetic stack embedded into a CPW. Moreover, we have established a method of characterization of electrical pulses in terms of current and energy [9]. Figure 1 shows MOKE images of ferrimagnetic Ta(3)Pt(5)Co(1)Gd(1)Ta(2)Pt(1), where the number between parentheses corresponds to thickness in nm. This sample was shaped by UV lithography into a 4 x 6 μm^2 film. We have found that magnetization reversal of this sample can be achieved by lower current densities as compared to previously studied Co samples, in concordance as what was reported in Ref. [6] for ns pulses.

Further details and comparison between different materials will be presented in the conference. These results can help deepen our understanding of the SOT mechanism in the ps scale and also pave the way for new SOT-based spintronics devices [10, 11].

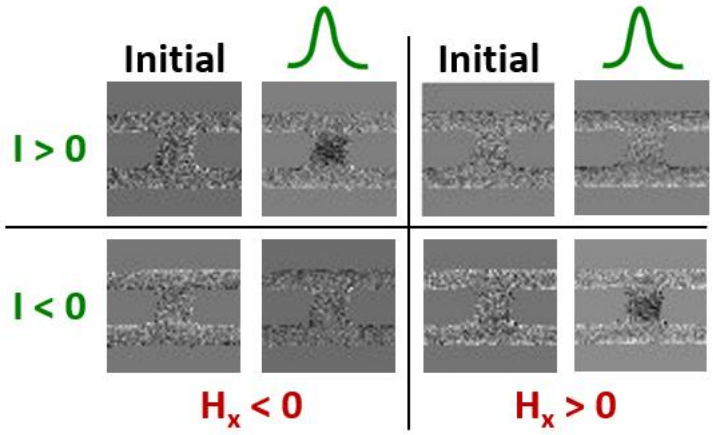

Figure 1: MOKE images of single-pulse switching of CoGd by SOT, for different configurations of current (I) and external in-plane magnetic field (H_x).

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Universal switching of magnetization by circularly-polarized phonons

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In our experiments performed at the free-electron laser facility FELIX [1], we expose ferrimagnetic GdFeCo samples grown on c-cut sapphire (Al_2O_3) substrates to infrared and ultrashort circularly-polarized pulses. A single pulse, with wavelength λ = 21 μm and sufficiently short in duration, switches the magnetization deterministically via the ultrashort heating of the ferrimagnet (Fig. 1a). By extending the duration of the pulse to more than ≈1.5 ps, we observe a clear failure of all-optical switching, with only randomized domains being formed (Fig. 1b). In contrast, upon exposing the sample to hundreds of circularly-polarized 3.3-ps-long pulses (λ = 21 μm), we achieve switching of magnetization. This is made clearer by scanning the laser pulses across the sample surface (Fig. 1c). This unambiguously indicates that a different mechanism is at the root cause of switching at these longer pulse durations [2].

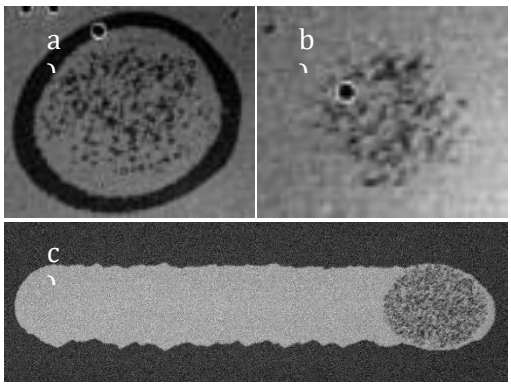

Fig. 1 (a)-(b) Magneto-optical images showing the effect of a single pulses (wavelength λ = 21 μm) with duration τ = 0.7 ps and 3.3 ps respectively. (c) Magneto-optical image showing the effect of sweeping circularly-polarized pulses (λ = 21 μm, τ = 3.3 ps) across the sample at a speed of 5 μm/s.

Upon tuning the central wavelength of the optical pulses, we observe that the switching efficiency depends dramatically on the pumping wavelength (Fig. 2). The efficiency of switching scales with the absorption spectrum of the substrate, which correlates to the spectrum of transverse optical phonons in the sapphire substrate.

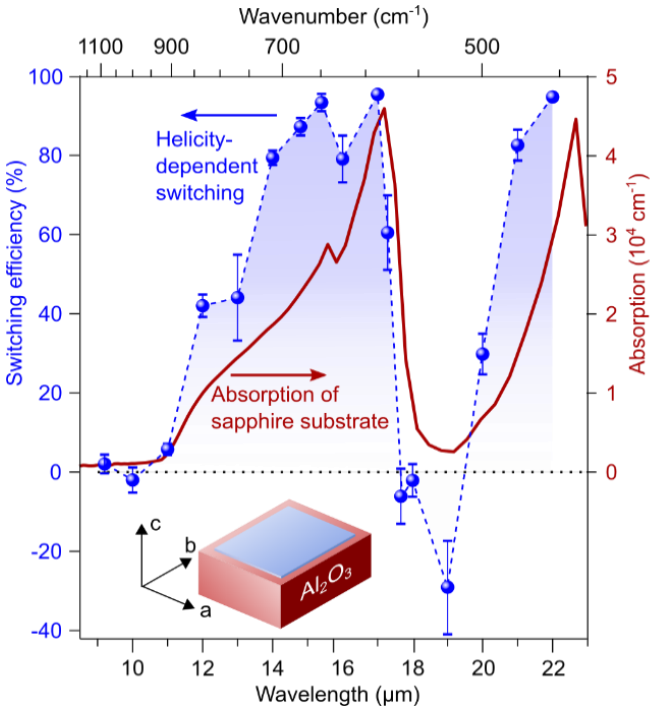

Fig. 2 Spectral dependence of the helicity-dependent magnetic switching measured in the GdFeCo-based nanostructure grown on a sapphire substrate, obtained with a sweeping speed of 50 μm/s. Overlaid are the respective absorption spectra characteristic of the substrate.

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Magnetisation dynamics of epitaxial Co_2MnSi Heusler thin films and Co_2MnSi/X/Co_2MnAl Heusler bilayers for coupling investigations

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Magnetic materials with low Gilbert damping are mandatory for future spintronic and magnonic applications. Half-metallic Co_2Mn-based Heusler compounds are of particular interest for such applications mainly due to their 100% spin polarisation at the Fermi level and the associated ultralow Gilbert damping in the 10^{-4} range [1].

Motivated by the observation of multiple peaks in ferromagnetic resonance (FMR) spectroscopy measurements ascribed to the co-existence of various chemical (dis)order types in Co_2Mn-based Heusler compounds, our study aims at exploring the coupling between adjacent Heusler layers of slightly different magnetic properties. To investigate coupling effects in a controlled model environment, we study the behaviour and interaction of $L2_1$-ordered Co_2MnSi and B2-ordered Co_2MnAl Heusler thin films mediated by metallic and non-metallic interlayers. For the purpose of this study, Co_2MnSi and Co_2MnAl single films as well as Co_2MnSi/X/Co_2MnAl multilayers with X = {Mn, MgO} were investigated.

The epitaxial Heusler films in this study were fabricated by molecular beam epitaxy as described in [2]. Crystalline quality and chemical ordering were confirmed by transmission electron microscopy techniques as shown in figure 1 (A). FMR measurements were performed on the thin films in order to study the magnetisation dynamics. We investigate the magnetic coupling mediated by (non-)metallic interlayers of various thicknesses, see an example in figure 1 (B). Comparisons of the magnetization dynamics in different configurations lead us to the conclusion that the dynamics are governed by biquadratic coupling between the Co_2Mn-based Heusler thin films.

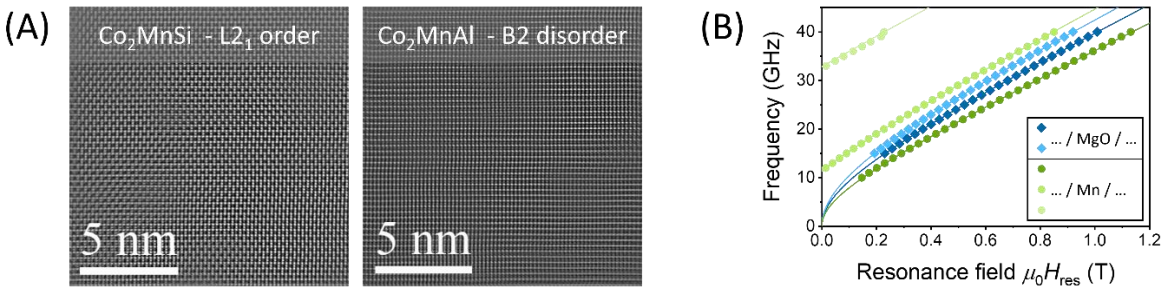

Figure 1: (A) HAADF-STEM micrographs: (dis)ordering types in the two Heusler compounds in this study. (B) In-plane FMR measurements: different behaviour for the Co_2MnSi/*X*/Co_2MnAl with interlayers *X* = {Mn, MgO}.

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Laser-induced ultrafast magnetization reversal in STT spin valves

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The manipulation of magnetic materials without the use of magnetic fields is of great fundamental and technical interest. The discovery of spin-transfer torque (STT) [1,2] allowed us to control the magnetization direction electrically in magnetic devices within nanoseconds, which paved the way for non-volatile applications such as spin-transfer-torque magnetoresistive random access memory (STT-MRAM). However, current-induced STT switching below a few hundred picoseconds with low power consumption while maintaining high thermal stability is still challenging. Ultra-short optical pulses can also be used to manipulate the magnetization direction without a magnetic field, which is called all-optical switching (AOS). So far, only specific materials containing ferrimagnet such as GdFeCo have shown ultrafast AOS [3,4]. Thus, these methods to manipulate magnetization have been mostly developed independently within the fields of spintronics and ultrafast magnetism. In this study, we demonstrate sub-picosecond magnetization reversal of a Co/Pt ferromagnetic layer induced by a single femtosecond laser pulse within a common [Co/Pt]/Cu/[Co/Pt] perpendicular spin-valve structure [5,6]. We also reveal that the mechanism behind this phenomenon could be understood in the analogy of current-induced STT switching [6,7].

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Dynamical spin-charge conversion probed by thz-tds spectroscopy: From transition metals to ultrathin epitaxial $bi_{1-x}sb_x$ topological insulators

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Recently Terahertz (THz) spintronics has emerged as a prominent field at the frontier between magnetism, spintronics, and photonics. Spin-to-charge conversion in femtosecond laser excited magnetic heterostructures may provide high efficiency and wide-bandwidth terahertz emission with a magnetically controllable polarization state[1]. The origin of this THz emission has been assigned to the generation of a spin-polarized current from a ferromagnetic source after a femtosecond laser excitation and subsequent conversion of the spin current into a transverse charge current[2]. Two main mechanisms may be involved: the Inverse Spin Hall Effect (ISHE) and the Inverse Rashba- Edelstein Effect (IREE) as provided by topological surface states.

In that mind, the occurrence of metallic quantum states at the surface of 3D topological insulators (TIs) has opened exciting new functionalities in spintronics owing to their topological protection and spin-momentum locking (SML) properties. The combination of band inversion and time reversal symmetry (TRS) results in a peculiar spin texture in momentum space. The resulting spin-charge conversion (SCC) efficiencies in topological surface states (TSS) combining strong spin-orbit coupling (SOC) and SML is expected to be at least one order of magnitude larger compared to the spin Hall effect (SHE) of 5*d* heavy metals. SCC has been then demonstrated in a range of Bi-based TI compounds, including bismuth selenide Bi_2Se_3, bismuth telluride Bi_2Te_3, $Bi_2(Se,Te)_3$ or $Bi_{1-x}Sb_x$ (BiSb). To benefit fully from IREE, the charge currents should be confined in the surface states and any current flowing through the bulk states should be avoided. The prerequisites are hence i) a sizeable bandgap typically larger than 0.2 to 0.3 eV, and ii) a perfect control of the Fermi level position, usually achieved by stoichiometry and/or strain engineering. We will report on our detailed investigation of the surface state SML properties of ultrathin (111)-oriented $Bi_{1-x}Sb_x$ epitaxial films. They exhibit a topological phase as recently confirmed by our angular-resolved photo-emission spectroscopy (ARPES) measurements[3] as well as in-plane spin texture more recently evidenced by SARPES. Moreover, the SCC mediated by the BiSb surface states is probed at the sub-picosecond timescale using an adjacent metallic Co layer acting as a spin injector.

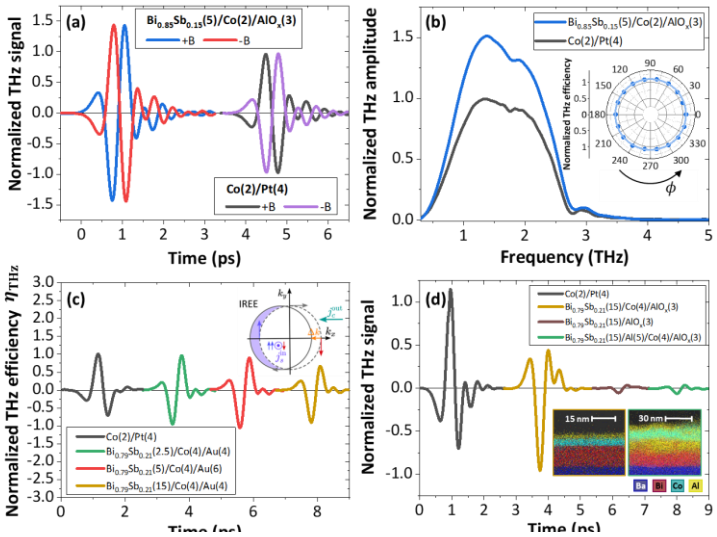

Figure 1: SCC and THz emission from $Bi_{1-x}Sb_x$/Co bilayers.

(a) THz time-trace from $Bi_{0.85}Sb_{0.15}(5)/Co(2)/AlO_x(3)$ for ±B compared to Co(2)/Pt(4) (grown on high resistivity Si substrates). THz phase reversal is a signature of SCC-mediated THz emission.
(b) Spectral components of the THz emission from $Bi_{0.85}Sb_{0.15}(5)/Co(2)/AlO_x(3)$ and Co(2)/Pt(4) for +B. Inset) Normalized THz efficiency ηTHz dependence on the azimuthal angle ϕ for $Bi_{0.85}Sb_{0.15}(5)/Co(2)/AlO_x(3)$.
(c) THz efficiency η THz as a function of the $Bi_{0.79}Sb_{0.21}$ layer thickness (2.5, 5 and 15 nm) compared to Co(2)/Pt(4).
(d) THz signals from $Bi_{0.79}Sb_{0.21}(15)/Al(5)/Co(4)/AlO_x(3)$, $Bi_{0.79}Sb_{0.21}(15)/AlO_x(3)$, $Bi_{0.79}Sb_{0.21}(15)/Co(4)/AlO_x(3)$ on BaF_2 and Co(2)/Pt(4). Inset) Fluorescence map obtained from a TEM cross-section for $Bi_{0.79}Sb_{0.21}(15)/Co(4)/AlO_x(3)$ (brown frame) and $Bi_{0.79}Sb_{0.21}(15)/Al(5)/Co(4)/AlO_x(3)$ (green frame) grown on BaF_2 for the elements and the color code given below the maps.

Unprecedentedly large SCC is measured with efficiencies beyond the level of optimized Co/Pt systems. Part of the result from THz emission measurement are summarized on figure 1. Our results indicate that surface state related IREE is the mechanism responsible for SCC mechanism. Tight-binding calculations and linear response theory account for our findings.

Our results address the role of spin-textured hybridized Rashba-like surface states offering unprecedented SCC efficiency despite the breaking of the TRS symmetry due to the local exchange interactions imposed by the magnetic contact. These results hold promise for efficient and integrated THz spintronic emitter based on BiSb.

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Single Femtosecond laser Pulse Induced In-Plane Magnetization Switching in Ferrimagnetic Gd_xCo_{100-x} alloys

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Single-shot all-optical helicity-independent switching (AO-HIS) is demonstrated and systematically studied in in-plane magnetized Gd_xCo_{100-x} thin films. Compared to their perpendicular magnetized (PMA) counterparts : (i) the deterministic single-shot toggle magnetization switching is observed for a much wider window of concentration ranging from x=10 to 25%; (ii) in case of $Gd_{25}Co_{75}$, AO-HIS could be observed for thicknesses ranging from 5 to 30 nm with a reversal threshold fluence that non-linearly increases as the thickness increases; (iii) time-resolved magneto-optic Kerr effect measurements show that the time needed to reach thermal equilibrium is similar to the one with PMA. Our results shows that AO-HIS in in-plane magnetized Gd_xCo_{100-x} provide extended potential for applications on opto-spintronic and studies on ultrafast magnetism with respect to their PMA counterpart.

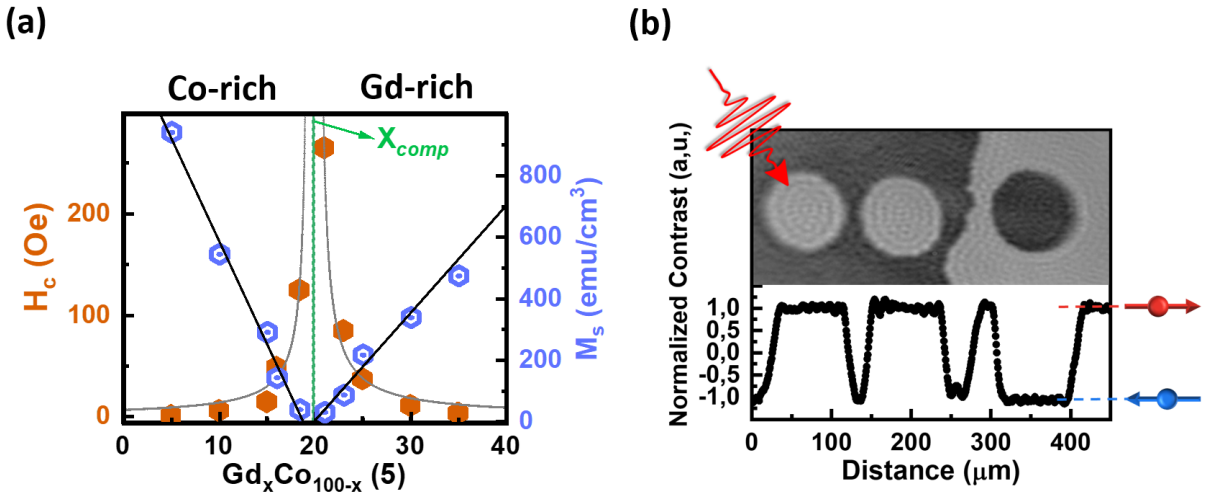

Figure 1: The magnetic properties as a function of Gd content in Glass/Ta (3 nm)/Gd_xCo_{100-x} (5 nm)/Cu (1 nm)/Pt (3 nm). (b) For a $Gd_{15}Co_{85}$ thin film starting from a two-domain magnetic state of opposite direction along the easy axis, Kerr images and normalized contrast cross-section after three single laser shots inducing AO-HIS. The arrows' direction indicates the Co sublattice's magnetization direction.

Bulk spin-orbit effect in single rare earth-transition metal alloy on the magnetization switching

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In the early work[1], we have shown the spin-orbit torque (SOT) switching on the single TbCo layer with or without the heavy metal (HM) in different thickness to identify the damping-like torque of bulk SOT effects generated in the TbCo layer. Here, we prepared two structures for the detailed investigation as shown in Figure 2(a) left. For both structures, the interplay of self-torque and the spin orbit torque generated in HM was clearly observed. Since the spin hall angle is opposite from the bulk TbCo, the addition of SOT from top W and self-torque from $Co_{70}Tb_{30}$ leads to smoothly enhanced switching efficiency when the thickness of $Co_{70}Tb_{30}$ is increased. On the other hand, the competition of SOT from bottom W and self-torque in $Co_{70}Tb_{30}$ of W/$Co_{70}Tb_{30}$ devices was revealed by increasing the thickness of $Co_{70}Tb_{30}$. The comparison of two W-based structures reveals two critical points: (1) The self-torque effect in TbCo requires a threshold thickness (6 nm) to establish and (2)The sign of spin hall angle in $Co_{70}Tb_{30}$ is independent of the layer position which is very different from the traditional heavy metal and we attributed it to the bulk spin hall effect. Next, we measured the effective DMI effect for both systems by the loop shift measurements[2]. With the increased Tb_{30} Co_{70} thicknesses, we can clearly observe that the effective DMI fields are enhanced accordingly, as shown in Figure 3. It has been reported that the thick ferrimagnets have additional contribution of DMI effect from the bulk nature[3], whatever the materials of the interfaces on the ferrimagnetic layer are, the consistent increment of the DMI effect is observed. According to our results, we find that an clear positve correlation between TbCo thickness and effective DMI fields, meanning that the bulk properties is dominated. These results broaden the scope of spin-orbitronics and provide a novel avenue for developing single-layer-based SOT memory with simplified architecture and improved scalability.

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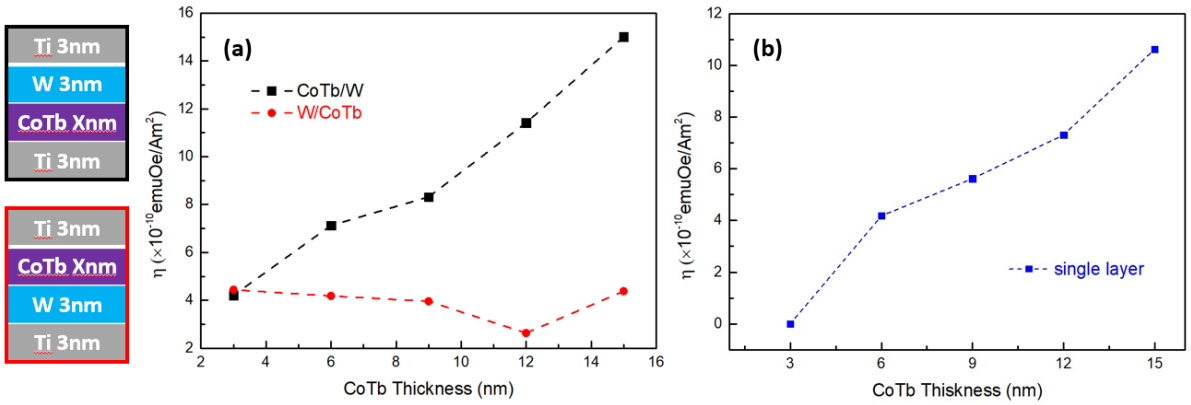

Figure 2 SOT switching efficiency comparison for (a) W-based system and (b) single layer system

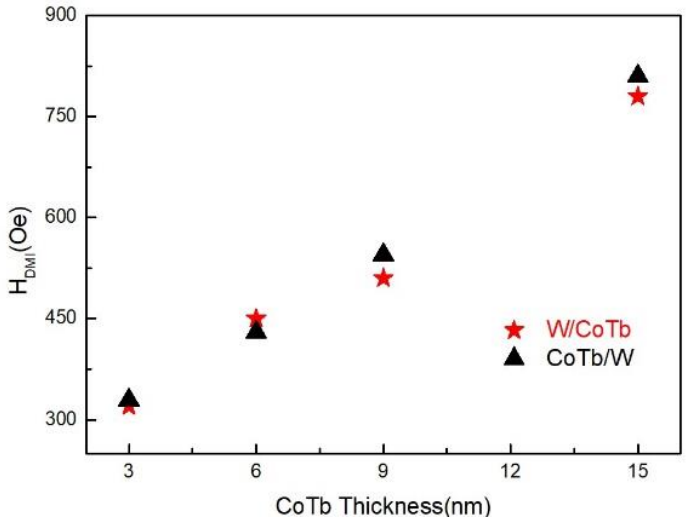

Figure 3 Effective DMI field as a function of CoTb thickness.

Underscreened Kondo cloud in superconductor

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The Kondo effect is a fascinating many-body phenomenon where the conduction band electrons screen a magnetic impurity. One of its interesting outcomes is the formation of a screening cloud called the Kondo cloud around the impurity. Recent studies have revealed that the mere presence of a magnetic impurity in superconductors induces a quantum phase transition in the system. This transition arises due to the competition between the Kondo energy scale and the superconducting energy gap [1].

In this study, we investigate the behavior of an underscreened Kondo cloud created by a large-spin impurity in the presence of a superconducting energy gap. We employ Numerical Renormalization Group (NRG) and Density Matrix Renormalization Group (DMRG) methods to analyze the compensation κ, which measures the screening imparted by the clouds, and the spatial profile of the clouds.

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Layer-resolved Vector Magnetometry using generalized magneto-optical ellipsometry

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A major challenge in nano-scale magnetism and spintronics today revolves around the experimental confirmation and precise understanding of spatial magnetization configurations or spin structures in homogeneous and non-homogeneous materials. This is crucially important because very relevant fundamental phenomena and cutting-edge devices rely heavily on the presence of specific spin structures at the nanometer scale, particularly within the depths of their structures [1,2]. Therefore, a spatially resolved identification of the spin- or magnetization-vector is the ultimate goal for any kind of characterization methodology. Here, we consider a subset of this ultimate or full characterization challenge and attempt to determine the magnetization depth profile by means of magneto-optical measurements, which by itself is a highly demanding task. Previous efforts have successfully distinguished magneto-optical signals originating from individual layers within multilayer sequences, but these studies only measured one magnetization component and thus, did not achieve vector magnetometry [3]. However, generalized magneto-optical ellipsometry (GME) has been demonstrated to allow full vector magnetometry using a single reflection experiment and measurement sequence [4,5]. In addition, we successfully demonstrated recently that this GME methodology has the ability to distinguish between two magnetic layers, not only if they generate comparable magneto-optical signal levels, but even if they produce vastly different signal strengths [6].

In this work, we determined the magnetic depth profile of a multilayer sample with two ultrathin ferromagnetic (FM) layers and its evolution with an applied field *H*. For this purpose, we utilized GME measurements and recorded the entire optical reflection matrix ***R*** as a function of the applied field, containing pure optical and magneto-optical signals. Considering the fact that ***R*** contains two independent values for the signal produced by each magnetization component at every field value, namely the real and imaginary components of the complex valued magneto-optical elements of ***R***, and the fact that the different vector component signals exhibit different symmetry, we were able to achieve layer-separated vector magnetometry. Upon utilizing samples, whose field response is determined by magnetization vector rotations, such as epitaxial magnetic films and multilayers, the signals produced by the different magnetization components are correlated, even if different layers show different rotation dependencies and lead to non-collinear states. Correspondingly, GME acquired data sets are overdetermined and allow for a robust methodology to achieve layer resolved vector magnetometry, enabling us to disentangle its magnetic depth profile.

In order to achieve this, we have first designed and grown a set of FM/Non-Magnetic (NM)/FM epitaxial multilayers, with the two FM thin layers having different anisotropy strengths, but the same easy axis orientation. Also, we have varied the NM interlayer thicknesses *t* in a series of such samples, as shown in Fig. 1(a). Specifically, our magnetic bilayers consist of Co (2 nm)/$CoRu_{0.41}$ (t nm)/$CoPt_{0.14}$ (2.1 nm) multilayers, which are in-plane uniaxial and generally exhibit lateral uniform states that are well described by one specific macrospin vector for each FM layer. The different anisotropy strength of the two FM layers allowed us now to systematically induce non-collinear states by orienting the sample with its easy axis (EA) at an angle φ_0 away from the applied field direction, as indicated in Fig. 1(a). In this design, we can tune the level of magnetic alignment in between the layers, both by applying a field and by means of the NM layer thickness *t*. When *t* is small, the FM layer will be strongly coupled, given that the NM layer material

is nearly ferromagnetic by itself, and the sample will behave in a collinear way independent from the field strength. As t increases, we obtain a range of collinear to non-collinear magnetic behavior. This set of samples with different magnetic depth profiles enabled us to test the capabilities of our layer-resolved vector magnetometry methodology, based upon GME measurements and associated data analysis schemes. One exemplary result for our samples is shown in Fig. 1(b) for the specific case of t = 8 nm, for which the two FM layers are fully independent. This can be corroborated by our data analysis, which shows that the magnetization vectors of each of the FM layers rotate and switch independently with the applied field strength, and only exhibit a collinear alignment for H = 0, because the easy axis of both films are aligned by means of the specific sample epitaxy that we have selected and experimentally verified.

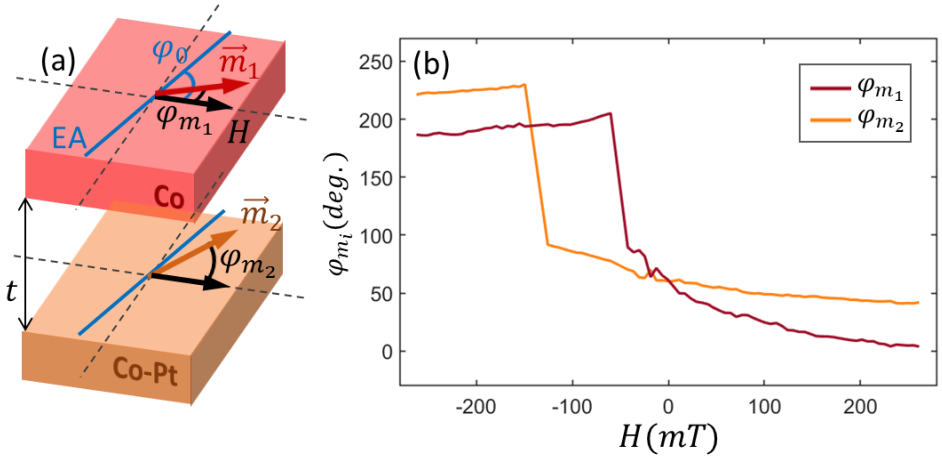

Figure 1: (a) Schematic of the FM/MN/FM structure used in this study indicating the FM materials, which were utilized, as well as the EA and magnetization vector orientations and their angles with respect to the applied field direction (φ_0, φ_{m_1} and φ_{m_2}). Also, the NM interlayer thickness t is indicated; (b) layer-resolved magnetization vector orientation in a sample with t = 8 nm versus the field strength H, extracted from GME measurements for fields of decreasing strength and $\varphi_0 = 65$ deg.

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ADVANCED DESIGN OF MTJ FOR THE APPLICATION OF SPIN TORQUE NANO-OSCILLATOR

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Spin torque nano-oscillator (STNO) is a fascinating spintronic device used in that impacts on wireless communication, recording technology, and data processing in the future. Its exhibits outstanding performance in generating a broad spectrum of frequencies spanning from gigahertz to terahertz, by utilizing spin-transfer torque (STT). The work provides a theoretical investigation of the angular dependence on the critical current density required for the high-performance generation of stable signals in CoFeB/MgO/CoFeB MTJ-STNO. To conduct this investigation, an atomistic model combined with spin accumulation is employed, which differs from most previous theoretical studies that utilized micromagnetic simulation coupled with Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation. Our approach opens the possibility to consider the penetration of the spin current in MTJ depending on the thickness of the MgO layer and the relative angle between magnetization in pinned and free layers. Furthermore, it allows for explaining a comprehensive understanding of the interfacial surface between CoFeB and MgO film layers. We found that by increasing the size of the magnetization angle, the critical current density applied to the STNO was decreased due to the increase in torque between the magnetization in the free layer and the spin current. At the same time, increasing the relative angle leads to a decrease in STNO frequency. Nevertheless, the STNO system operates at relatively high frequencies above 21 GHz at each angle. Moreover, the system quickly reaches a stable state within 1 ns after introducing the charge current density.
It can be concluded that the relative angle between magnetizations has a significant role in achieving stable and high frequencies within sub-nanosecond. This study is an important milestone toward applying STNO for the next generation of data and communication technologies.

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Enhancing control of exceptional points through nonlinearity in coupled magnetic oscillators

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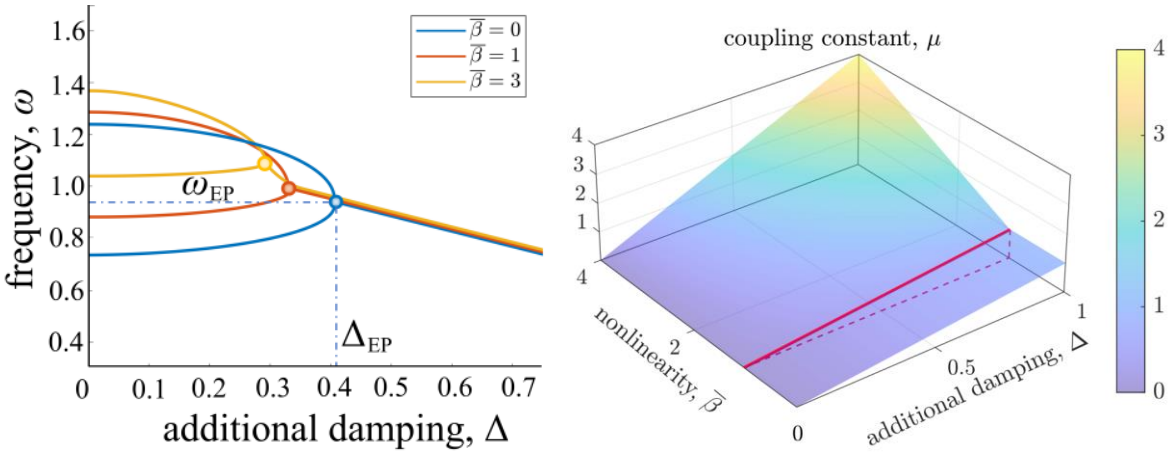
Exceptional points (EPs) are points in the parametric space of physical systems where the eigenvalues and eigenvectors coalesce [1]. Such degeneracies are intrinsic to non-Hermitian systems that possess PT -symmetry. Spectra of these systems undergo a transition from real to complex in EPs, where spontaneous symmetry breaking occurs. An EP can be achieved in PT -symmetric systems by changing the value of gain and loss and coupling strength between the system's parts [2]. Recently, they have also been predicted and experimentally demonstrated in spintronic [3] and magnonic systems [4-7], where intrinsic damping can be compensated by the spin transfer torque (STT). The connection between parts of a magnonic system with gain and loss has the nature of dipole and exchange interaction. It is well-known that these interactions are directly proportional to the distance between the coupled parts. A position of an EP, in turn, directly depends on the coupling strength [5]. Therefore, to control the parameters of the appearance of an EP, it is necessary to change the geometrical dimensions of the system, such as the thickness of the magnetic layers, the width of the waveguides, or the shape of the resonators. This means that varying of the EP's position is unreachable within the same structure. It is, therefore, crucial to find an additional parameter that the position of an EP can be shifted.

We have considered a system of two ferromagneticnormal metal structures coupled by a magnetic field, where an exceptional point arises due to the balance of magnonic gain and loss because of the spin-transfer torque. The position of the EP can only be altered by changing the physical parameters in magnonic systems, such as the width of its layers or the distance between elements, so it is important to find a parameter for EP's tuning. We employed two coupled Landau-Lifshitz equations to analyze the system, considering intrinsic damping and STT. This led us to a system of coupled Duffing type equations, a standard model for describing nonlinear dynamic systems, along with such models as, for example, the Lorenz and van der Pol oscillators. By using these equations, a broad range of physical systems and processes can be modeled - from pendulums and electrical circuits to cell proliferation dynamics and climate change. Our analysis shows that the nonlinearity parameter β directly impacts the position of the EP (Fig.1a). An increase in β leads to decreasing of the additional damping Δ which directly affects on the EP's frequencies (Fig. 1a). However, altering the position of the EP without changing the structure parameters results in a decrease in the resonant amplitude due to the hysteresis effect. We examine how the additional damping Δ depends on the coupling constant μ and the nonlinearity parameter β. In the linear case, where $\beta = 0$, the dependence of the EP formation on μ is linear, specifically, $\mu = \Delta$. As previously stated, an increase in the nonlinear coefficient β results in the EP forming at lower values of Δ, which also becomes apparent as the coupling parameter μ changes. The dependence of $\mu(\Delta)$ takes the form of $\mu(\Delta) = A(\beta)\Delta$, where $A > 1$ is the steepness of this characteristic (see Fig.1b). Therefore, with greater coupling (i.e., smaller distance between magnetic structures), the presence of nonlinearity results in a decrease in insertion loss, at which the EP appears.



(a) (b)

Figure 1: (a) Real parts of the eigenfrequencies dependence on additional damping Δ in presence of the nonlinearity β; (b) A dependence of the coupling strength constant μ on the additional damping Δ in the presence of nonlinearity parameter.

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Separation of heating and magneto-elastic coupling effects in surface acoustic wave-enhanced magnetic domain wall creep motion

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Surface acoustic waves (SAWs) show significant potential for energy-efficient control of magnetic domain wall (DW) creep motion owing to the magneto-elastic coupling effect [1]. However, the SAW-induced heating can also contribute to the DW motion [2]. In this work, the heating of a SAW device was measured locally using an on-chip Pt film as a thermometer within the SAW beampath. Fig.1 shows the diagram of the devices. Two interdigitated transducers (IDTs), whose centre frequency is 48 MHz, were patterned on opposite ends of a 2-mm-wide stripe of Ta(5.0)/Pt(2.5)/Co(0.9)/Ta(5.0) thin film (thicknesses in nm). The film was prepared by dc magnetron sputtering onto a lithium niobate substrate, which can support the propagation of SAWs. Results show that a temperature increase of ~10 K was observed within the SAW beampath with the application of SAWs at the centre frequency of 48 MHz and a total RF power of 21 dBm (Fig. 2a). DW velocity was also measured using Kerr microscopy at various temperatures or in the presence of SAWs (Fig. 2b). With a 10 K increase in temperature and no SAWs applied, DW velocity increases from 33±3 μm/s (at room temperature) to 104±8 μm/s at an external magnetic field of 65 Oe. Travelling SAW-assisted DW velocity (116±3 μm/s) is slightly higher than that with a 10 K temperature increase suggesting that heating plays the major role in promoting DW motion, whereas the DW motion is significantly enhanced (418±8 μm/s) in the presence of standing SAWs suggesting that magneto-elastic coupling effect is more important than heating in this case [3].

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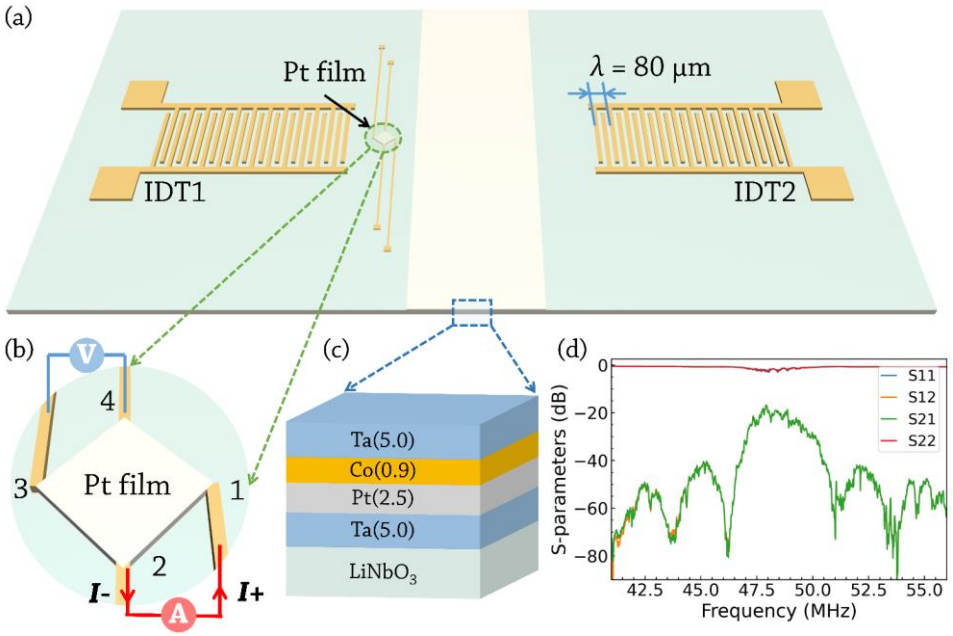

Figure 1: (a) Schematic diagram of the SAW device (not to scale). (b) Schematic diagram of the electrical transport measurements using Pt film. (c) The structure of the Ta(5.0)/Pt(2.5)/Co(0.9)/Ta(5.0) (nominal thicknesses in nm) thin film. (d) S-parameters for IDTs used to launch SAWs.

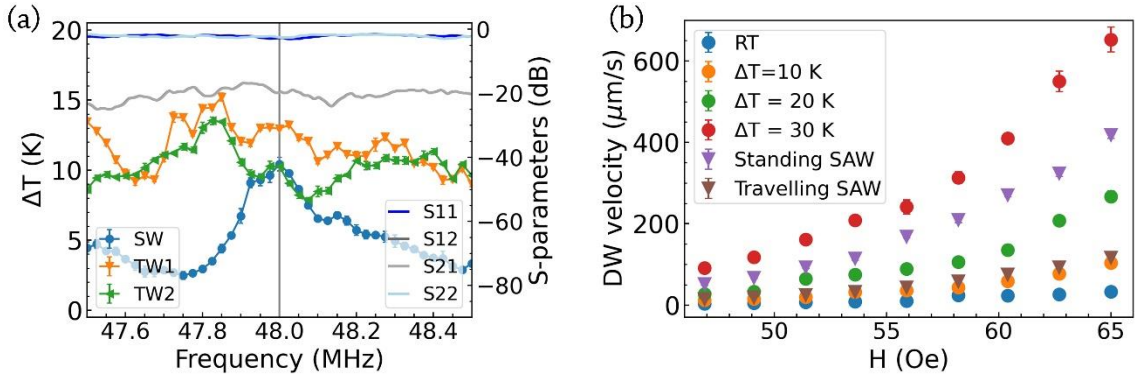

Figure 2 (a) Temperature changes of the device plotted against applied SAW frequency. TW1, TW2 and SW denote travelling SAWs form IDT1 IDT2, and standing SAWs, respectively. (b) Domain wall velocity at different temperatures or in the presence of SAWs plotted against the applied magnetic field.

The optimal condition of L10/A1 FePt magnetic nanodot for the application in Heated Dot Magnetic Recording technology

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Heated Dot Magnetic Recording (HDMR) is proposed as the challenging magnetic recording technology that combines a heat-assisted writing process and bit pattern media to achieve ultra-high areal density beyond 10 Tb/in2. This work focuses on investigating the magnetic properties of FePt material, which is a promising candidate for HDMR technology, using atomistic simulation with the rescaling technique [1]. The FePt core/shell structure is modeled by setting the ordered L10 and disordered A1 structural phases in the core and shell grain regions, respectively. The A1 phase represents structural defects that are inevitable during the experimental fabrication process and becomes crucial for the realistic model. Therefore, the effect of grain geometry, structural phase ratio, and grain size on the magnetic properties of L10/A1 FePt are investigated to consider the optimal criteria of core/shell FePt.

Initially, it was observed that the cylindrical shape demonstrates high thermal stability and a high magnetization. This is attributed to the highest composition of atoms in the L10 structural phase compared to other geometries such as cubes, hexagons, and spheres. Subsequently, the influence of L10 and A1 structural phases on magnetic properties are examined and the results show that an increase in the proportion of L10 content leads to the conversion of the initially soft magnetic material into a hard magnetic material. However, an efficient increase in areal density in magnetic recording technology can be achieved by a reduction in grain size, which reduces the energy barrier and against thermal stability. To achieve optimal conditions for FePt magnetic grains, it is advisable to maintain a core/shell ratio of 0.75 or higher and ensure that the grain size is not smaller than 6 nm. This combination effectively addresses thermal instability concerns.

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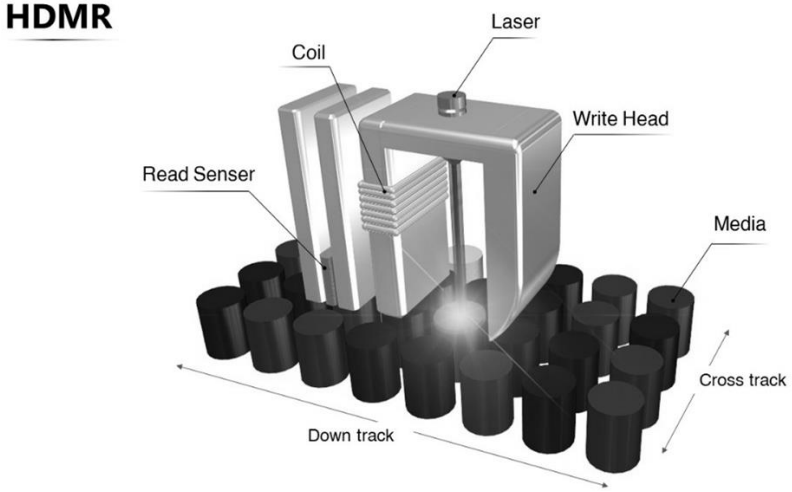

Figure 1: Schematic diagram of Heated Dot Magnetic Recording technology

Skyrmion diffusion controlled by alternating current excitations

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Magnetic skyrmions are considered promising candidates for implementing probabilistic computing devices since they respond strongly nonlinearly to external stimuli and feature multiscale dynamics [1].

The implementation of such probabilistic computing relies on thermal excitation and diffusive movement of the magnetic skyrmions within thin films, which exhibit pinning due to sample defects [2]. Especially the combination of skyrmion diffusion and current-induced motion has been shown to be useful in Brownian reservoir computing devices [3].

As thermal skyrmion diffusion is often slow due to the impact of pinning, a depinning procedure can be key for applications. Procedures suggested so far provide depinning, but at a relatively high energy cost, due to for example the use of external magnetic fields. Therefore, a low-energy procedure is desirable. To reach such a regime of very high diffusion, we propose and experimentally demonstrate depinning by applying alternating currents to the sample [4].

In particular, we show that the energy landscape is effectively flattened and diffusion drastically enhanced for sufficient current densities and by tuning the applied the excitation frequency even outside of the flow regime. This can therefore be useful to reduce pinning effects and accelerate non-conventional computing devices.

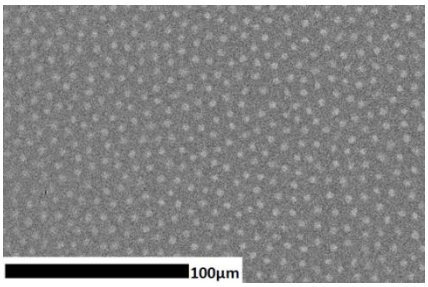

Figure 1: Skyrmion system as studied experimentally.

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Laser-induced magnetization switching in $NiCo_2O_4$ thin films

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Ultrafast spin dynamics have attracted attention because they are expected to be implemented in next-generation nonvolatile spintronic devices with a laser after the discovery of the sub-picosecond demagnetization in a Ni foil reported in 1996 [1]. During the past two decades, there are a number of studies, in which ultrafast spin dynamics have been observed in various magnetic materials in both fundamental and applied perspectives.

In this presentation, we will report laser irradiation effects on ferrimagnetic $NiCo_2O_4$ thin films. Thanks to the perpendicular magnetic anisotropy, this material is a candidate of new spintronics materials. The metallic nature was confirmed based on the finite Fermi edge in our x-ray photoemission spectroscopy measurements. To observe the ultrafast dynamics and laser irradiation effects, we developed our own pump-probe setup for two experimental studies: time-resolved magneto-optical Kerr microscopy and magneto-optical Kerr microscopy with laser pulse irradiation. We used Pharos (Yb: KGW) as a light source whose wavelength is 1030 nm and pulse duration is 200 fs.

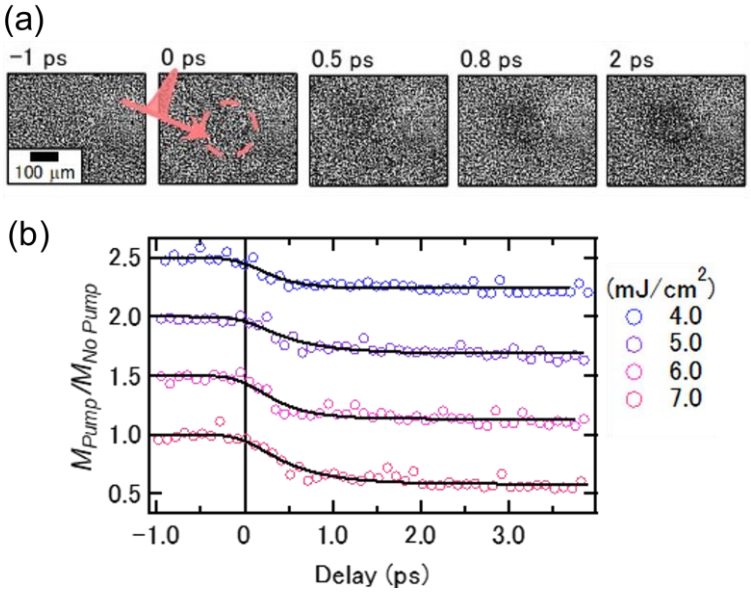

Figure 1 (a) Magnetic domain images of $NiCo_2O_4$ under laser irradiation collected at several delay points. (b) Pump-fluence dependent dynamics of the sample magnetization estimated by the contrast of the image of the laser-irradiated area [2].

Firstly, to observe the dynamics of laser-irradiated magnetic domains of the $NiCo_2O_4$ thin film, we combined the two systems, i.e., the pump-probe method and magneto-optical Kerr microscope. With this setup, the ultrafast demagnetization within 0.4 ps was observed (Fig. 1) [2]. This is an unexpected behavior in view of the half-metallic electronic state predicted by the first principle calculation [3]. On

the basis of the three-temperature model, it is less likely that the spin temperature increases in a half-metal because of the small spin-electron interaction. However, the actual spin polarization of a $NiCo_2O_4$ thin film observed by the tunnel magnetoresistance was found to be small (approximately 0.7 [4]) and, therefore, the spin-electron interaction can effectively be large and can lead to the fast demagnetization within 1 ps in $NiCo_2O_4$ thin films observed in our measurements.

Secondly, we also observed magnetic domains after laser irradiation by using a magneto-optical Kerr effect microscope with a laser pulse accumulation. Figure 2 shows the magnetic domains of $NiCo_2O_4$ thin films after the linearly polarized laser irradiation. While only multi-domains due to the laser heating was observed at 300 K, all-optical switching (AOS) was observed above 380 K with irradiating linearly polarized multiple pulses. As the temperature of $NiCo_2O_4$ thin films approaches to the Curie temperature, the coercive field and saturation magnetization decrease and thereby the magnetic domain size increases. We argue that this temperature-dependent domain size is crucial for AOS rings formations above 380 K. The precise relationship between the magnetic domain size and AOS ring is, however, still elusive.

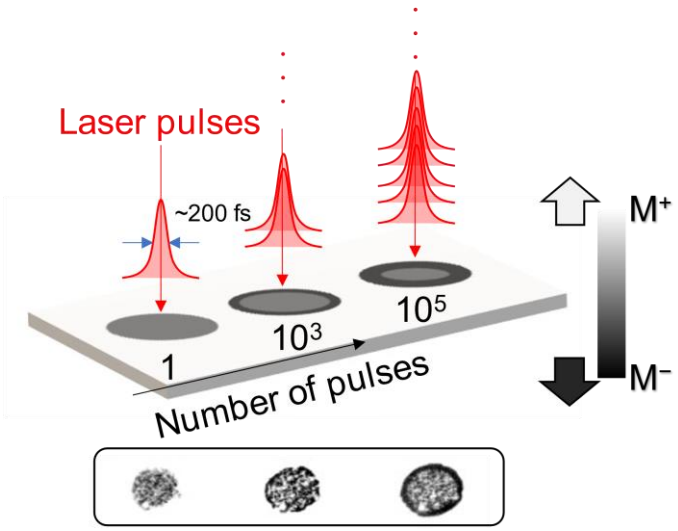

Figure 2: The magnetic domains of the $NiCo_2O_4$ thin film after laser pulse irradiation at 380 K [5].

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Effects of pattern dimensions on displacement sensitivity of positioning sensors based on magnetic tunnel junction arrays

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Magnetic positioning sensing is an advanced method of displacement detection, in which the object position is transduced into variations in local magnetic field in the area of the sensor. A typical configuration consists of magnetic field sensor and a positioned object with micromagnet. The positioned object induces a highly non-homogeneous magnetic field. The magnetic sensor detects local magnetic field variations, associated to displacements of this object. The main advantage of the method is a possibility to detect mechanical displacement "behind a solid wall", without having either optical or mechanical access to the positioned object. The method is very actively developed nowadays, and multiple manufacturing companies provide solutions of remote sensing based on magnetic positioning approach.

Linearity of the signal to the displacements is a key performance characteristics of these systems. However, active elements in most of magnetic sensors are micro-devices, patterned by lithography. In addition, many applications require compensation of signal offsets and drifts. To fulfil this requirement, a set of devices should be connected in a single electrical circuit (ex. Wheatstone bridge). In that case, the special gaps between the active elements of the sensing devices are unavoidable. In this work, we will discuss effects of pattern width, length and gap size on the resulting positioning transfer curves of the magnetic positioning systems, based on magnetic tunnel junction arrays.

When the magnetized object is positioned in a close proximity to the active element of magnetic sensor (the distance between the sensor and the object is smaller than the sensor pattern size along the positioning direction), the special gap between the patterns of the MTJ arrays leads to non-linearity of the signal to the positioning displacements. The positioning sensitivity becomes reduced, when the magnetized object is positioned in a close proximity to the sensor array, over the area of the special gap. The variations in pattern length provide accurate control of the positioning sensitivity and ranges of signal linearity with displacement. An increase of the distance between the sensor and the object positioning trajectory reduces the non-linearity of the positioning signal, caused by special gaps between the sensor patterns. The optimal conditions for improvement of signal linearity were found by adjustment of this distance together with the sensor pattern length.

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Phase Coexistence and Ultrafast Dynamics of Magnetic Order in Metamagnetic FeRh Nanostructures

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Metamagnetic materials are outstanding candidates for finding and exploiting new functionalities and emergent phenomena on small spatial and temporal scales. For instance, the transition from the antiferromagnetic to ferromagnetic order in sub-micron-wide FeRh wires becomes greatly asymmetric when comparing the heating and cooling cycles [1,2]. This recovery of the abrupt transition in nanostructures enables fast low-energy control of magnetic properties, leading to potential applications, for instance, in sensing, spintronics, and magnetic resonance imaging. Local control of phase coexistence in FeRh micro- and nanostructures is therefore essential. It is achievable by using magnetic field, strain, or femtosecond laser pulses. Here, we discuss the associated mechanisms for systems ranging from continuous thin films [3] through patterned structures to self-assembled nanoislands [4], which sustain the metamagnetic transition.

Furthermore, we show the dynamic response of the electronic and magnetic order to ultrafast laser excitation can be followed by time-resolved photoemission electron spectroscopy [5], which unlike techniques probing the total magnetization in the sample provides a direct comparison to the dynamic response of the structural order. The transient photoemission spectra of FeRh thin films show that the FM phase of FeRh, characterized by a minority band near the Fermi energy, is established in less than 500 fs after the laser excitation [5].

Finally, we use ultrafast x-ray diffraction to study the laser-induced magnetostructural phase transition in FeRh nanoislands. The comparison with a comparable continuous FeRh film reveals less tetragonal distortion of unit cells in the ferromagnetic phase, which originates from an in-plane expansion of the nanoislands lowering the transition temperature in thermal equilibrium. We observe an intrinsic 8 ps timescale for nucleation of ferromagnetic domains in both samples [6]. Unlike the excitation of continuous films, the more homogeneous optical excitation of nanoislands results in a faster nucleation-dominated phase transition.

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Parsing the ultrafast non-local spin transfer in Gd-based Ferrimagnetic spin valves

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Optically induced ultrafast demagnetization can simultaneously give rise to a non-local spin transfer because of the conservation of the angular momentum. This mechanism can be manifested in a ferrimagnetic spin valve [1] via an exotic phenomenon of the all-optical ultrafast switching of the ferromagnetic layer. It is believed that the spin current originated from ultrafast demagnetization of the Gd sublattice (the widely discussed "-dM/dt" mechanism) impact dominantly in this nonequilibrium process of spin cooling that lift the critical slowing down[2]. Very recently, it is demonstrated that ultrafast switching can even be realized in the rare-earth free spin valves[3], the authors believe that the ultrafast demagnetization of the Co lattice can generate spin current with an opposite alignment that motivates the unidirectional P to AP switching.

Based on the above observation, both Co and Gd can produce a spin current that traverses the whole spin valve to transfer the spin momentum. A question naturally emerges: can the spin current originating from the Co be treated on the same footing as the Gd within a "-dM/dt" mechanism and a ballistic transporting manner?

To solve this problem, we study the static and dynamic behaviors upon femtosecond laser pulse stimulation in a Co-rich spin valve. The stacks structure are listed below: Glass(substate)/Ta(5)/Pt(3)/$[Pt(1)/Co(0,5)]_4$/Cu(10)/Gd25%FeCo(5)/Ta(5) where numbers between brackets are thicknesses in nm and the Co/Pt multilayer is referred to as the reference layer and the top GdFeCo layer is referred to as the free layer. In this Co-rich spin valve, we managed to observe the single pulse unidirectional "P to AP" and "AP to P" switching of the free layer (figure 1) at different fluences, which is absent in the Gd-rich spin valves but can be observed in the rare-earth free spin valves.

Exploiting the Time-resolved MOKE imaging technique with a quarter wave plate, we measured the dynamics of each layer's magnetization with different pumping fluences. Figure 2 shows the dynamics starting from the P (left) and AP (right) configurations respectively with pumping fluence of 3.61 mJ/cm^2. For the AP to P switching, the onset of the reversal takes place around 600 fs and crosses the zero within 1 ps. The line shape indicates the switching process consists of a non-equilibrium spin cooling followed by an equilibrium gradual recovery. Whereas for the stimulation starting from the P state, it is obvious that a robust critical slowing down plateau exists for 5 ps after the fast demagnetization process and then starts to reverse. So, we could estimate that the onset of the switching is around 5 ps, which is much slower than the situation of the AP to P switching.

This discrepancy strongly points to an implication of the coexistence of two different mechanisms that generate the ultrafast spin current. We anticipate that the 5ps time delay after the onset of remagnetization of the CoPt layer indicates a more diffusive manner of the corresponding thermal spin current which needs more time to traverse the 10 nm thick Cu layer in between the spin valve; whereas the much more rapid spin current coming into play within 1 ps indicate a more ballistic behavior of the spin current which may come from the non-thermal spin-polarized hot electrons excited by the rapid heating.

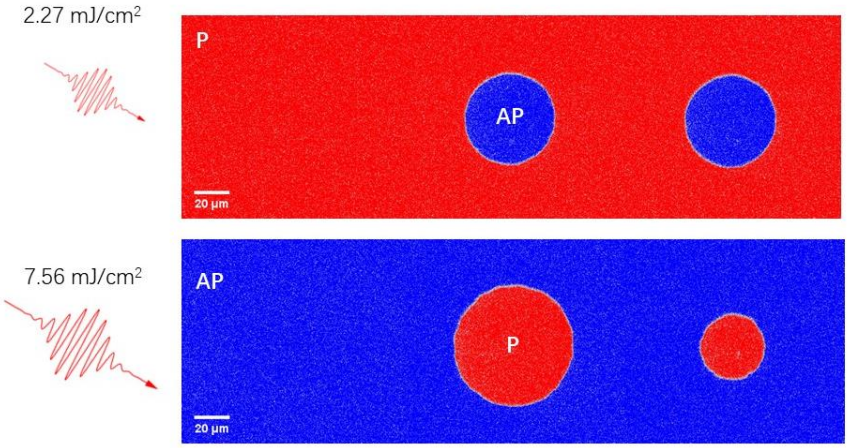

Figure 1: single pulse switching for the GdFeCo free layer upon different pumping fluences. The P configuration is defined as the CoFe moment of free layers parallel with the Co moment of the reference layer.

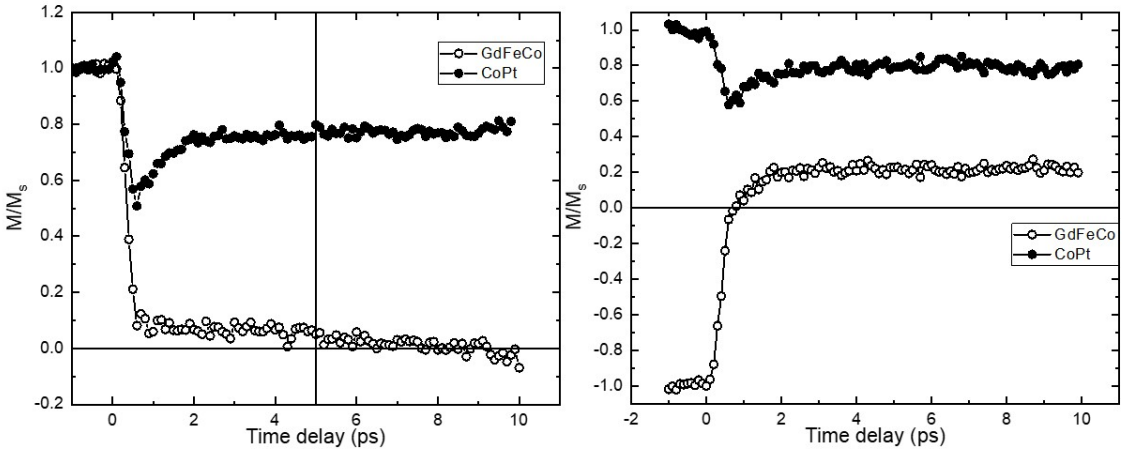

Figure 2: TR-MOKE dynamics of the magnetizations of both free and reference layers starting from P (left) and AP (right) configuration.

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