Abstract Book

Spin Dynamics at the Nanoscale and its Applications: A Symposium in Honor of Andy Kent

Date: September 23-24, 2022
Location: New York University
Venue: Greenberg Lounge at Vanderbilt Hall
Address: 40 Washington Square South, New York, NY 10012

Organizing committee
- Daniel Stein (NYU, Department of Physics and Mathematics)
- Eric Fullerton (UC San Diego)
- Axel Hoffmann (University of Illinois at Urbana-Champaign)
- Stéphane Mangin (University of Lorraine)
- Jonathan Sun (IBM Research)

Invited Speakers
- Enrique del Barco (UCF)
- Geoffrey Beach (MIT)
- Jamileh Beik Mohammadi (Loyola University)
- Stefano Bonetti (Stockholm University)
- Gabriel Chaves-O’Flynn (Polish Academy of Sciences)
- Eugene Chudnovsky (CUNY)
- Chiara Ciccarelli (University of Cambridge)
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- Daniel Gopman (NIST)
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- Axel Hoffmann (University of Illinois Urbana-Champaign)
- Roopali Kukreja (UC Davis)
- Chris Leighton (University of Minnesota)
- Kai Liu (Georgetown University)
- Luqiao Liu (MIT)
- Ferran Macià (University of Barcelona)
- Stéphane Mangin (University of Lorraine)
- Hans Nembach (NIST)
- Hendrik Ohldag (University of California/LBNL)
- Hideo Ohno (Tohoku University)
- Barbaros Oezylmaz (National University of Singapore)
- Stuart Parkin (Max Planck Institute)
- Mustafa Pinarbasi (Magnetics Technology)
- Shaloo Rakheja (University of Illinois)
- Dafiné Ravelosona (CNRS)
- Laura Rehm (NYU)
- Juan-Carlos Rojas-Sánchez (CNRS)
- Ulrich Rüdiger (RWTH Aachen University)
- Christopher Safranski (IBM Research)
- Ivan Schuller (UC San Diego)
- Javad Shabani (NYU)
- Jonathan Sun (IBM Research)
- Mingzhong Wu (Colorado State University)
- Shufeng Zhang (University of Arizona)
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Spintronics nonvolatile working memory based on magnetic tunnel junction (MTJ) has been shown to reduce the power of CMOS-based microprocessors orders of magnitude, making it suitable for IoT [1], AI, and other applications. Such MTJs are scalable down to 2.3 nm without resorting to new materials [2-5], an essential feature for future development. When we make MTJs volatile, a new computing scheme emerges that could solve problems potentially more efficiently than silicon-based digital information processing. We have made a proof-of-concept probabilistic computing circuit that can solve optimization problems using stochastic, hence volatile, MTJs [6]. The time scale involved in these stochastic MTJs has been addressed [7, 8]. It also provides a means to experimentally access the switching exponents under magnetic field and current [9]. If time allows, I will touch upon a neuromorphic approach to mimic a “spiking neural network” where a short time constant is involved [10].

Work done in collaboration with S. Fukami, S. Kanai, B. Jinnai, and the CSIS team and supported in part by, JST-OPERA JPMJOP1611, JST-CREST JPMJCR19K3.

References:

Spin Transfer Torque Magnetic Random Access Memory Technology and Applications

M. Pinarbasi\textsuperscript{1}

\textsuperscript{1}Magnetics Technology

Spintronics technology and ecosystem have been developing during the past few decades following the discovery of the giant magnetoresistive effect (GMR) in 1988. Spin Transfer Torque MRAM (STT-MRAM) is the latest product application utilizing spintronics technology. STT-MRAM is a non-volatile memory technology with fast read and write speeds, low power requirements, scalability and easy integration to CMOS processing. Magnetic tunnel junction (MTJ) is at the heart of the STT-MRAM and one of its unique attributes is that it can be designed to enhance specific performance parameters to meet product requirements. However, these parameters are not independently controlled and their careful optimization is essential. For example, write current and stability of the storage layer are directly coupled leading to undesirable trade-offs between endurance (speed) and retention. These topics along with a method that improves the retention without effecting the other parameters will be discussed.
Spin-transfer-torque switchable magnetic tunnel junction is an enabling device for novel approaches to computing. After well over a decade of intense development by many manufacturers, it has found its place in technology and product offerings in spin-transfer-torque switched magnetic random access memory (STT-MRAM). We will give an overview of the device physics with our current understanding, with an emphasis on device and materials physics underpinning switching performance in memory technologies, and the likely requirements for future generations in related applications space[1-3]. Key considerations include switching current, speed, and data-retention trade-off, and the need to seek more efficient charge-to-spin conversion mechanisms. We demonstrate one such method in a structure we call a double spin torque magnetic tunnel junction, where we can achieve a significant reduction in switching current [3] and increase in switching speed. Finally, we touch on some nascent applications ideas involving the magnetic tunnel junction as a compact and power-efficient CMOS backend-compatible entropy source for probabilistic computing, and the device physics related to sub-nanosecond stochastic bit-stream generation [4], with potential applications in computing schemes beyond von Neumann architecture.

References:

Stochastic Magnetic Actuated Random Transducer Devices Based on Perpendicular Magnetic Tunnel Junctions

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Neuromorphic systems are of great interest for modeling and solving complex problems, offering an alternative to conventional deterministic computers \cite{1}. They generally aim to emulate the functionality and structure of the human brain and thus require many independent true random noise signal sources. In addition, cryptography applications also require high quality random numbers \cite{2}. In recent years, the stochasticity of spin-transfer-torque switching of magnetized tunnel junctions has gained interest for such applications. Focusing on in-plane magnetized tunnel junctions with low energy barriers, the devices investigated thus far have fast thermally driven random fluctuations \cite{3,4}. However, these types of devices are highly susceptible to small changes in temperature as well as device parameters like the shape of the free layer and material parameters.

Here we show the room-temperature operation of medium energy barrier ($\Delta=39 \text{[5]}$) perpendicularly magnetized magnetic tunnel junctions (pMTJs) in the ballistic switching limit (ns duration pulses) and discuss why their operation is much less sensitive to temperature and material parameters. In the ballistic limit the resulting junction state---antiparallel (AP), high resistance or parallel (P), low resistance---is random mainly because of the thermal distribution of the initial magnetization state. We denote this a stochastic magnetic actuated random transducer (SMART) device because the pulse activates the junction to generate a random bit stream, much like a coin flip. We analyze the stochastic nature of our SMART devices by comparing their statistics to that expected of Bernoulli trials (see Fig. 1). We also test our bit stream with the NIST statistical test suite for random and pseudorandom number generators which investigates their suitability for cryptographic applications. We find that by whitening the bit stream with only one XOR operation, we pass all NIST tests and, in addition, that we can also successfully sample a uniform distribution which is commonly used in computations that require random numbers. Our results demonstrate that medium energy barrier pMTJs are very promising candidates for true random number generation for neuromorphic computing due to their easily controllable characteristics, while being robust towards environmental changes and material parameter variations.

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References:

Figure 1: Distribution of the number of switched attempts for the AP to P transition of a 40 nm diameter pMTJ device at $T_{\text{bath}} = 295$ K. (a) Number of switched attempts $N_s$ in a sample size of $N = 100$ versus the sample number $S$. The straight line in the plot represents the switching probability $p = 0.5027$ of the whole data set ($N_t \sim 8*10^6$). (b) Histogram of the switched events $N_s$ of the same data set. The line in the plot shows a binominal distribution of a slightly weighted coin flip with a probability of $p = 0.5027$. 
Resonance and Non-resonance Excitation of Spin Waves through Surface Acoustic Waves

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Spin waves in magnetic materials are coherent dispersive waves, typically in the low GHz frequency regime and with wavelengths of hundreds of nanometers. Interest in spin waves is motivated by the possibility of its integration into nano-scale devices for high-speed and low-power signal processing. However, generation of spin waves with high amplitudes—and their detection—is challenging due to the mismatch of wavelengths with electromagnetic waves in free space, which is of the order of several centimeters.

In this talk, I will review some recent experiments on the coupling of surface acoustic waves (SAW) and spin waves using X-ray Photo-Emission Electron Microscope (XPEEM). The main observations are: i) the SAW generation up to 3 GHz of large amplitude spin waves (up to 25 degrees) over large distances (up to several millimeters) in several materials—Cobalt, Nickel and a Heusler alloy (Fe₃Si) [1], ii) the control of SAW interference patterns and its generation of spin wave interference patterns [2] iii) the possibility of generation non-resonance spin waves and its difference with resonance excitation [3] and iv) the possibility of moving magnetic domains at the SAW velocity [4,5].

References:

Hybrid Magnon Modes

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Magnons are the fundamental excitations of magnetically ordered materials and span frequencies from GHz to THz at wavelengths down to the nm-regime. Because of their convenient frequencies and wavelengths, they have been considered for computational applications by encoding information into their phase and amplitude. Concurrently, magnons readily interact with a wide variety of different excitations, including microwave and optical photons, phonons, and other magnons. Such hybrid magnon dynamic excitations have recently gained increased interest due to their potential impact on coherent information processing [1]. This in turn opens new pathways for hybrid quantum information systems [2]. I will discuss two specific examples, where we developed fully integrated devices to demonstrate strong magnon-photon coupling in scalable coplanar devices [3], as well as magnon-magnon hybrid modes, which reveal new damping-like torques due to coherent spin pumping [4].

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References:

The Dzyaloshinskii-Moriya interaction (DMI) gives rise to chiral magnetic structures, which include chiral spin chains and skyrmions. DMI requires broken inversion symmetry and can exist in the bulk of a material as well as at interfaces. The presence of DMI gives rise to a non-reciprocal frequency-shift for spin-waves, which are propagating perpendicular to the applied magnetic field direction (Damon-Eshbach geometry). This frequency-shift can be probed with Brillouin light scattering spectroscopy (BLS) and can be used to determine the strength of the DMI [1]. Quantized spinwaves have been measured in nanowires and small magnetic elements. The mode profile is generally determined by a balance between Heisenberg exchange and dipolar energy. The presence of DMI and the associated non-reciprocal spinwave propagation can strongly influence the quantized mode structure.

In my talk, I will discuss the impact of the DMI on quantized spinwaves in Co nanowires [2]. We sputter deposited Ta(4 nm)/Pt(3 nm)/Co(1.8 nm)/Al(2 nm)/Pt(3 nm) thin films on oxidized Si wafers and used electron beam lithography to define arrays of nanowires with width-spacing ranging from 100 nm to 400 nm. We characterized the samples with ferromagnetic resonance spectroscopy and SQUID magnetometry to determine the Heisenberg exchange, saturation magnetization, Gilbert damping and anisotropy. We measured the arrays with Brillouin Light Scattering spectroscopy (BLS) with the external magnetic field perpendicular to the plane of incidence. During the scattering event between a photon and a spinwave, the component of the momentum in the plane of the sample needs to be conserved. As such, only spinwaves propagating in the plane of incidence are probed. We find that the frequency-shift remains constant for all wires width, if the long axis of the wires is in the plane-of-incidence but is smaller for the narrower wires in the orthogonal configuration. In the first case, the BLS probes spinwaves propagating along the wires and the frequency-shift corresponds to the strength of the DMI. In the latter geometry, the BLS is sensitive to the standing spinwaves perpendicular to the long axis of the wire. The decrease in the frequency-shift with wires width, see figure 1, can be understood by taking into consideration: 1) The two counter-propagating spinwaves, which form the standing spinwave, have the same frequency but different wavevectors $k_1$ and $k_2$ in order to follow energy conservation. This results in a dynamic magnetization profile, which can be described by $m(y) = \exp\left(\frac{i(k_1+k_2)}{2}y + \frac{d}{2}\right) \times \cos(k_n (y + \frac{d}{2}))$, $d$ is the wire width, $k_n = \frac{k_1-k_2}{2} = \frac{n\pi}{d}$ and $n=0,1,2, \ldots$. [3] 2) The scattering cross section for the BLS, which is given by $I(q) = |m(q)/m_0|$, where q is given by the scattering geometry [4]. 3) The large linewidth of this thin ferromagnetic layer in contact with Pt. We have modelled the expected frequency-shift taking the above considerations into account and achieved good agreement with the experiment.
References:


Figure 1: Frequency-shift vs. wire width measured with BLS at 45 degree angle of incidence.
The dimensionality of physical systems plays an important role in determining various equilibrium and non-equilibrium properties. We theoretically investigate the fundamental differences of hysteresis, magnetization dynamics, and spin transport properties between two-dimensional (2D) and three-dimensional ferromagnets.

For 3D magnetic materials, an excellent approximation is that the saturation magnetization $M_s$ is a constant, independent of the applied magnetic field and other external forces if the temperature is sufficiently below the Curie temperature. This approximation greatly simplifies the calculation of hysteresis and magnetization dynamics. For 2D magnets, however, the approximation fails, due to intrinsic strong spin fluctuation of 2D systems. For example, when the sum of the external field and the anisotropy field is zero, the divergence of the number of gapless magnons suppresses long-range order known as the Wigner-Mermin theorem, or $M_s$ becomes zero. The 2D magnet will then evolve to a new equilibrium state, not by the magnetization rotation, but by the rapid change of $M_s$ at a critical magnetic field. We propose a generalized magnetization dynamic equation for 2D magnets beyond Landau-Lifshitz-Gilbert equation.

Let us first consider a simple Stoner-Wohlfarth (SW) model of single domain particles. For two dimensional magnets at finite temperature, the SW model must be extended to include the change of the amplitude of magnetization with the applied magnetic field. We show several fundamentally different hysteresis loops between 2D and 3D magnets. The magnetization switching diagram known as the asteroid figure in the conventional SW model becomes highly temperature dependent and asymmetric with respect to the transverse and longitudinal magnetic fields. Next, we study the magnetization switching of a 2D single domain particle. Depending on the strength of the magnetic field, the magnetization has both transverse and longitudinal motion which leads to a much faster switching time. The origin of the faster switching of the 2D magnet is again due to spin fluctuations in which the quantum nature of the creation of the low energy magnons governs the dynamics.

Finally, we also address the magnetization switching by a current-driven spin torque. We propose a quantum approach that explicitly includes the spin fluctuation by the quantum statistics of magnon spectra. We find that the spin fluctuation substantially reduces the critical spin torque at high temperatures. The result implies that the 2D magnets may have an advantage in terms of electrically manipulating magnetization states for spintronic applications.
In the first part of my talk, I will discuss the synthesis, by laser-assisted chemical vapour deposition, of centimetre-scale, free-standing, continuous and stable monolayer amorphous carbon, topologically distinct from disordered graphene. Bulk amorphous materials have been studied extensively and are widely used, yet their atomic arrangement remains an open issue. Unlike in bulk materials, the structure of monolayer amorphous carbon can be determined by atomic-resolution imaging. Extensive characterization by Raman, X-ray spectroscopy and transmission electron microscopy reveals the complete absence of long-range periodicity and a threefold-coordinated structure with a wide distribution of bond lengths, bond angles, and five-, six-, seven- and eight-member rings. Direct measurements confirm that such a material is insulating, with resistivity values similar to those of boron nitride grown by chemical vapour deposition. Free-standing monolayer amorphous carbon is surprisingly stable and deforms to a high breaking strength, without crack propagation from the point of fracture. Such excellent physical properties could prove useful for permeation and diffusion barriers in applications such as magnetic recording devices and as copper diffusion barrier.

In the second part of my talk, I will discuss ferromagnetism in Co-doped semiconducting black phosphorous (BP) up to room temperature. Ferromagnetic semiconductors combine electric field tunability with nonvolatility. Yet, despite decades pursuing such co-functionality, room-temperature ferromagnetic order remains a challenge. In Co-doped gate tunable BP, carrier-mediated room-temperature ferromagnetism is corroborated by its performance as a robust ferromagnetic contact in semiconducting tunnelling spin-valves and by a large anisotropic magnetoresistance. We demonstrate electric field selection of the dominant majority/minority spins, allowing both gate-controllable inversion and supression of tunnelling magnetoresistance on demand.
Self-torque in Ferrimagnetic Thin Films

J-C Rojas-Sánchez

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The strong spin-orbit coupling of heavy metals was pioneered to manipulate the magnetization of a magnetic layer by spin-orbit torque. This can be considered as the beginning of spin-orbittronics and allowed the development of new non-volatile memories. Better efficiency was also anticipated using two-dimensional systems with spin textures such as Rashba interfaces or topological insulators [1]. More recently, attention has been focused on magnetic materials with strong SOC such as GdFeCo ferrimagnet [2]. They can also efficiently generate spin currents, and spin currents of different symmetries, spin anomalous Hall effect SAHE-like, and spin Hall effect SHE-like [3-5]. And one such symmetry, SHE-like, could produce what we could coin "self-torque" [2].

Rare earth-Transition metal (RE-TM) ferrimagnets offer a rich platform to study and exploit those new phenomena thanks to their various critical temperatures such as magnetic compensation temperature $T_M$, angular compensation temperature, $T_A$, and Curie temperature, $T_C$. Moreover, we have recently reported a new characteristic temperature, which we have called the switching temperature, $T_{\text{switch}}$, in the robust W/CoTb system. This temperature is higher than $T_A$ and lower than $T_C$ and increases with Co concentration [6].

I will show our study on ferrimagnetic FiM GdFeCo alloys. In these ferrimagnets, the strong SOC is given by the 5d band of rare earths. We demonstrate the giant spin current emission (SAHE+SHE) by GdFeCo from the current-induced modulation of the ferromagnetic resonance linewidth of NiFe in GdFeCo/Cu/NiFe. Overall efficiency is 25 times more important in GdFeCo/Cu/NiFe than in Pt/Cu/NiFe [2]. In the absence of the addition of the dc bias current, the symmetric contribution in this spin-torque FMR experiment is proportional only to the SHE-like symmetry [7].

The study of the self-torque is carried out by harmonic Hall voltage measurements in samples where the GdFeCo layer exhibits out-of-plane magnetization. We compare the self-torque in GdFeCo/Cu with torques induced by Pt or Ta in Pt/Cu/GdFeCo and Ta/Cu/GdFeCo [3]. Thus, these "self-torques" can be tuned by adjusting the spin absorption outside the GdFeCo layer. Moreover, taking advantage of the different characteristics temperatures in ferrimagnets [2,6,7], we show the features that differentiate self-torque from what we know so far, the "external" spin-orbit torque [2]. These results pave the way for new architectures to achieve switching by self-SOT and skyrmions manipulation.

Work performed with co-authors in Refs. 1, 2, 6 and 7. This work was partially supported from Agence Nationale de la Recherche (France) under contract ANR-19-CE24-0016-01 (TOPTRONIC), and related projects in Ref. 2, 6-7.

References:
Figure 1: Schematic of the current-induced modulation of the ferromagnetic resonance linewidth of NiFe experiment. We highlight that GdFeCo has a higher overall effective efficiency than Pt.
Understanding Elliott-Yafet Spin Relaxation at the Nanoscale in Non-Local Spin Transport Devices

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Injection of spins across ferromagnetic/non-magnetic metallic interfaces, and their subsequent relaxation in the non-magnetic metal, are foundational in spintronics. While Elliott-Yafet spin relaxation (a spin-orbit-mediated defect-based mechanism) is generally understood to dominate spin relaxation in light non-magnetic metals, perhaps surprisingly, there remain substantial gaps in our quantitative understanding. In particular, while the generalized Elliott-Yafet relation assigns specific spin relaxation probabilities to specific scattering sources, such as phonons, point defects, grain boundaries, surfaces, interfaces, etc., these specific probabilities are not well known, even in “simple” non-magnetic metals such as Cu and Al, and the theoretical support for this picture is incomplete.

In this talk, I will review a series of studies where we attempt to quantify spin relaxation probabilities at specific scattering sources in the elemental metals Cu and Al, using non-local spin-valves (NLSVs, Fig. 1(a)) [1-7]. Our findings strongly support the concept of a generalized Elliott-Yafet relation, determining specific spin relaxation probabilities for scattering by phonons, grain boundaries, and magnetic impurities in Cu [1-6]. The latter result in a spin transport version of the Kondo effect [1-6], which, remarkably, can also be cast in Elliott-Yafet form [3]. I will then progress to Al, in which our recent work reveals an unanticipated finite-size effect in phonon-induced Elliott-Yafet spin relaxation (Fig. 1(b)) [7]. This is explained in terms of enhancement of spin-orbit coupling and other phenomena at interfaces and surfaces [7]. In general, our results support remarkably broad applicability of the generalized Elliott-Yafet relation, provide accurate values for Elliott-Yafet spin relaxation probabilities at specific scattering sources, and reveal rich new associated phenomena at the nanoscale.

![Figure 1: (a) Scanning electron micrograph of a typical Co/Al NLSV. (b) Elliott-Yafet constant for phonon-induced spin relaxation (inverse spin relaxation probability) vs. Al thickness for Co/Al NLSVs. Note the](image-url)
order-of-magnitude finite-size effect, reproduced by our analytical and numerical modeling. Both figures are from Ref. [7].

References:

Almost two decades ago, our group had the dream to use x-ray microscopy to “see” the spin currents injected in non-magnetic layers from an adjacent ferromagnet. It was the heyday of research into giant magneto-resistance and spin currents in non-magnetic materials and spin transfer across interfaces was on everybody’s mind. Our expertise was in x-ray microscopy and we knew that it was the ideal tool to spatially separate magnetic moments across a non-magnetic/magnetic interface like e.g. Cu/Cu. However, for many years, we were not able to design an appropriate model system that would work magnetically and in the microscope.

It was at that time that we reached out the Kent group and Jordan Katine at HGST to help us. Thanks to their ingenuity and expertise we were able to detect the small magnetic moment injected from a PMA Co/Pt layer into a think Cu layer. For the first time we could directly assess how the very small injected magnetic moment of $2 \times 10^{-5}$ Bohr magneton is affected at the interface between the two layers and in the bulk of Cu. These experiments laid the foundation for our time resolved and high sensitivity microscopy work at the Stanford Synchrotron Radiation Laboratory as well as the Advanced Light Source in Berkeley over the next decade that included a lot of “firsts”, that I will review in this presentation. It underlines how important a strong collaboration between partners with complementary expertise is.

Figure 1: Sketch of the effect of a spin polarized current when injected from a FM to an NM
Pulling Magnetic Skyrmions out of Thin Air

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Magnetic skyrmions are topologically nontrivial spin textures with envisioned applications in energy-efficient magnetic information storage. Toggling the presence of magnetic skyrmions via writing/deleting processes is essential for spintronics applications, which usually requires a magnetic field, current injection, electric field, laser pulse, or thermal excitation. Using spin-polarized low energy electron microscopy (SPLEEM), we have previously demonstrated a chemisorption induced Dzyaloshinskii-Moriya interaction (DMI) and chirality switching in magnetic domain walls and skyrmions [1,2]. Here we demonstrate a field-free method to write/delete magnetic skyrmions at room temperature (Fig. 1), via hydrogen chemisorption/desorption cycles on Ni/Co/Pd/W(110) [3]. Supported by Monte-Carlo simulations, the skyrmion creation/annihilation is attributed to the hydrogen-induced magnetic anisotropy change on ferromagnetic surfaces. Furthermore, we have observed an ultrasensitive chirality switching in (Ni/Co)n multilayer induced by capping with only 0.22 monolayer of Pd [4]. The chiral evolution of a skyrmion during the DMI switching is also captured, where no significant topological protection is found as the skyrmion winding number varies. This corresponds to a minimum energy cost of < 1 attojoule during the skyrmion chirality switching. These results open up new opportunities for designing energy-efficient skyrmionic and magneto-ionic devices. This work has been supported in part by the NSF (DMR-2005108) and the SRC/NIST SMART Center.

Figure 1: Hydrogen-induced reversible writing/deleting of skyrmions. (a,b) SPLEEM image of Ni/Co/Pd/W(110), before/after the hydrogen exposure, showing hydrogen-induced skyrmion creation. Scale bar is 100 nm. (c) Compound SPLEEM image resolving the bubble-like domain in panel b as a skyrmion. (d) Experimentally determined arrow-array representation of panel c. (e) SPLEEM images showing reversible skyrmion writing/deleting over hydrogen on/off cycles (see arrows), scale bar is 200 nm.

References:

Skyrmions are whirls of magnetization in a ferromagnetic film shown in Fig. 1.

They were initially introduced in relativistic field theories by Skyrme as models of nuclear particles [2]. Belavin and Polyakov noticed [3] that all possible configurations of a fixed-length three-component vector field $\vec{n}(x, y)$ in a 2D plane can be divided into homotopy classes such that no continuous deformation of the field can bring it from one class to the other. This immediately applies to the Heisenberg exchange model with the Hamiltonian

$$
\mathcal{H} = -\frac{J}{2} \sum_{\langle ij \rangle} \vec{n}_i \cdot \vec{n}_j \\
= \frac{J}{2} \int dx dy \left( \frac{\partial \vec{n}}{\partial x} \cdot \frac{\partial \vec{n}}{\partial x} + \frac{\partial \vec{n}}{\partial y} \cdot \frac{\partial \vec{n}}{\partial y} \right), \quad (1)
$$

where $\vec{n}$ is the atomic spin (magnetization) in a 2D ferromagnet or the Néel vector in an antiferromagnet and $J$ is the exchange constant. It possesses a topologically protected minimum-energy solution in each homotopy class, characterized by the topological charge $Q = 0, \pm 1, \pm 2$, etc. At $Q = 1$ and $J$ normalized such that $\vec{n}^2 = 1$, they are skyrmion solutions shown in Fig 1:

$$
n_x = \frac{2\lambda r \cos(\phi + \gamma)}{\lambda^2 + r^2}, \quad n_y = \frac{2\lambda r \sin(\phi + \gamma)}{\lambda^2 + r^2}, \quad n_z = \frac{\lambda^2 - r^2}{\lambda^2 + r^2}. \quad (2)
$$
Here $\vec{r} = (x, y) = (r \cos \phi, r \sin \phi)$ is the radius-vector in the 2D plane, $\lambda$ is an arbitrary scaling parameter that can be interpreted as the size of the skyrmion, and $\gamma$ is an arbitrary chirality angle that equals 0 for the Néel skyrmion and $\pi/2$ for the Bloch skyrmion.

The energy of the $Q = 1$ skyrmion equals $4\pi\bar{r}^2$. In a continuous-field model it is independent of the skyrmion size $\lambda$ due to the scale invariance of the Hamiltonian (1). However, as soon as one takes the discreteness of the atomic lattice into account, the energy of the skyrmion acquires the dependence on $\lambda$, leading to its collapse [4]. In real magnetic films, skyrmions are stabilized by the Dzyaloshinskii-Moriya interaction (DMI) and the magnetic field. The typical size dependence of the skyrmion energy in the presence of DMI is shown in Fig. 2.

![Figure 2: Size dependence of the skyrmion energy in a square lattice of spacing $a$ for atomic spins of length $S$ interacting via ferromagnetic exchange of strength $J$, DMI of strength $A$, and Zeeman energy of strength $H$ (from Ref. [5])](image)

As the field goes up, the equilibrium size of the skyrmion goes down. At some critical field (see solid line in Fig. 2), skyrmions lose stability and collapse. This process is described by the classical Landau-Lifshitz-Gilbert dynamics in which the collapsing skyrmion loses energy by emitting spin waves [4,6].

However, when one begins to think about the final stage of the skyrmion collapse, a contradiction arises. Quantum uncertainty principle prohibits the skyrmion from collapsing into a point in the crystal lattice in the same manner as it prohibits an electron from falling onto a proton in the hydrogen atom. While it remains unclear whether quantum mechanics can fully stabilize a very small skyrmion as it stabilizes atoms, it is obvious that the energy of the skyrmion must be quantized, thus leading to a discrete spectrum of magnons emitted by a collapsing skyrmion.

This problem has a non-trivial solution [6] for an antiferromagnetic skyrmion described by the Hamiltonian (1) in a square lattice, which can be a good approximation for weakly coupled CuO layers of cuprate high-temperature superconductors. To quantize the Belavin-Polyakov skyrmion we treat the scaling parameter $\lambda$ as a generalized coordinate.
and write the generalized momentum as $\hat{p} = -i\hbar (d/d\lambda)$. This leads to the following quantum Hamiltonian

$$\mathcal{H} = \hat{p} \frac{1}{2M(\lambda)} \hat{p} - \frac{2\pi JS^2a^2}{3(\lambda^2 + a^2/6)}, \quad M = \frac{\pi\hbar^2}{Ja^2\ln\left(\frac{l/\sqrt{e}}{\sqrt{\lambda^2 + a^2/6}}\right)}, \quad (3)$$

where $M$ is the mass of antiferromagnetic skyrmion, with $l$ being the lateral dimension of the 2D spin system. Quantum energy levels of the skyrmion are shown in Fig. 3.

![Energy levels of antiferromagnetic skyrmion](image)

**Figure 3:** Energy levels of antiferromagnetic skyrmion obtained by numerical diagonalization of Hamiltonian (3) (exact) and by using Bohr-Sommerfeld quantization (from Ref. [6]).

Since the Belavin-Polyakov skyrmion is an exact solution of the 2D exchange model, its interaction with magnons is due to the discreteness of the atomic lattice that breaks the scale invariance of the model. In Ref. [6] we derived the interaction Hamiltonian and obtained the rates of transitions between quantized skyrmion states, see Table I.

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**Table I:** Transition rates in units $J/\hbar$ from state $m$ to state $n$ for $S = 1/2$ and $l = 1000$ (from Ref. [6]).

For a ferromagnetic skyrmion, both the total spin and the energy are quantized [7]. It would be interesting to design spectroscopy of skyrmions and test in experiment that...
the collapse of small skyrmions produces magnons with a discrete spectrum due to the quantization of skyrmion states.

I thank Andy Kent for his friendship and for sharing his physics ideas with me in the last twenty years. The work reported here was supported by the Grant No. DE-FG02-93ER45487 funded by the U.S. Department of Energy, Office of Science. It was done with my doctoral student Amel Derras Chouk in collaboration with Professor Dmitry Garanin.

References:

We present results of String Method calculations in nanodisks with different strengths, $D$, of the interfacial Dzyaloshinskii-Moriya interaction (iDMI). This method allows to identify minimum energy paths between metastable states and the transition states for thermal activated reversal. These systems are of great interest because of the potential of chiral structures for information transport and storage.

The iDMI favors the formation of domain walls and they acquire negative energy values beyond a critical value $D_{\text{crit}}$. In consequence, for small values of $D<D_{\text{crit}}$, a uniform magnetization has the lowest energy; at large $D>D_{\text{crit}}$, the cycloidal configuration is the ground state. The transition between purely uniform and cycloidal configuration can be smoothed by a variety of perturbations, such as external fields or geometric confinement, that allow for the formation of Skyrmions and other chiral textures. Skyrmions are topologically protected magnetization textures embedded in either the uniform or the cycloidal backgrounds, they contribute to the total topological charge of a magnetization texture ($Q$) with unitary values (1). In some contexts, a skyrmion is considered the combination of two merons, which are objects with $\frac{1}{2}$ topological charge.

The iDMI plays a role in setting the boundary conditions and stabilizing skyrmions. The continuum approximation requires that in infinitely extended films the magnetization has a conserved and integer total topological charge. This is not mandatory in confined geometries and $Q$ acquires a non-integer part which varies smoothly with changes on the magnetization. Nevertheless, this non-integer part can be evaluated with a line integral that follows the system edge; the integral part captures information of the total winding in the bulk.

We have investigated the energy landscape of ferromagnetic nanodisks with perpendicular magnetic anisotropy for different values of $D$ and identified three different regimes depending on the ratio of $D$ to $D_{\text{crit}}$. For $D/D_{\text{crit}}<1$, isolated skyrmions are destroyed by drifting motion towards the edge of the disk; for $D/D_{\text{crit}}\sim1$, the minimum energy path for skyrmion annihilation presents an intermediate state in which $Q$ changes by approximately $\frac{1}{2}$ which implies that merons are mediators for skyrmion annihilation; for $D/D_{\text{crit}}\sim1$, the energy landscape becomes very rough and presents many saddles and minima, and the existing minima are complex magnetization textures (See Fig.1).

Our String Method results shine light on a useful framework to classify the different energy minima after interpreting the magnetization textures in the large $D$ regime as...
networks of disclinations connected with tubular structures of zero topological charge. The transition states are associated with momentary collision of disclinations (see Fig 2) to allow for the re-accommodation of skyrmionic domains. These results highlight the importance of magnetic singularities in the thermally activated switching between micromagnetic states.

Figure 1: Energy values along the Minimum Energy Path between two chosen metastable states at large $D$. Maxima in this figure are transition states (saddles) for thermally activated switching between neighboring metastable states (minima). The largest maximum occurs when a meron reaches the boundary of the disk, secondary maxima occur when two distinct $-\pi$ disclination collide momentarily into a $-2\pi$ disclination.

Figure 2: Illustration of magnetic singularities in helimagnets (a) cycloid state (b) $p$ disclination (c) $2p$ disclinations, (e) $-p$ disclination (f) $-2p$ disclination (d) skyrmion in cycloidal background (g) a meron in a cycloidal background.

This research was supported in part by: the US National Science Foundation Grant No. DMR 1610416, and the National Science Centre Poland under OPUS funding grant No. 2019/33/B/ST5/02013 Polish National Science Center, project no. UMO-2018/30/Q/ST3/00416.
Fluctuating Domain Walls and Morphological Configurations in Chiral Magnetic Systems

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The fluctuating nature of magnetic domain morphology transitions has been the subject of intense study, given that such behavior may offer a directly observable means of understanding the physics of underlying magnetic phase transitions. At the same time, stochastic processes in condensed-matter systems have attracted significant interest for neuromorphic computing applications. Recently, we have reported on a domain morphology transition that occurs in the limit of low ferromagnetic exchange stiffness in thin-films with substantial perpendicular magnetic anisotropy and a moderate interfacial Dzyaloshinskii-Moriya interaction (e.g. see Fig. 1) [1]. The observed morphological transition was attributed to a severe reduction in the domain wall energy density. Building off these results, we discuss recent work in which we have employed temperature-dependent magneto-optic and AC susceptibility measurements to better understand the dynamics of this morphological phase transition. Besides temperature-induced changes in the domain periodicity, these measurements have indicated that these systems exhibit two distinct types of temperature-dependent fluctuations – faster-scale fluctuations in the domain wall positions and slower-scale fluctuations in the configuration of the overall domain morphology. While the domain wall fluctuations demonstrate properties of Brownian motion modified by a sporadic pinning potential, the slower-scale morphological fluctuations exhibit characteristics typically ascribed to more solid-like, collective dynamics.

References:


Figure 1: Remanent domain morphology of the [Pt/Co/Ni/Re]2 sample, where the Co layers were grown such that \( t_{\text{Co}} \) decreases by \( \sim 0.06\% \) when moving from left to right across the field of view. The center of the field of view corresponds to an approximate \( t_{\text{Co}} \) of 0.24 nm.
Control of Neel Vector with Spin-Orbit Torques in an Antiferromagnetic Insulator with Tilted Easy Plane

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Electrical manipulation of spin textures inside antiferromagnets represents a new opportunity for developing spintronics with superior speed and high device density. Injecting spin currents into antiferromagnets and realizing efficient spin-orbit-torque-induced switching is however still challenging. Because of the diminishing magnetic susceptibility, the nature and the magnitude of current-induced magnetic dynamics remain poorly characterized in antiferromagnets, whereas spurious effects further complicate experimental interpretations [1].

Recently, by growing a thin film antiferromagnetic insulator, α-Fe₂O₃, along its non-basal plane orientation, we realize a configuration where an injected spin current can robustly rotate the Neel vector within the tilted easy plane, with an efficiency comparable to that of classical ferromagnets [2] (Fig. 1). The spin-orbit torque effect stands out among other competing mechanisms and leads to clear switching dynamics. Thanks to this new mechanism, in contrast to the usually employed orthogonal switching geometry, we achieve bipolar antiferromagnetic switching by applying positive and negative currents along the same channel, a geometry that is more practical for device applications. By enabling efficient spin-orbit torque control on the antiferromagnetic ordering, the tilted easy plane geometry introduces a new platform for quantitatively understanding switching and oscillation dynamics in antiferromagnets (Fig. 2).

References:


Figure 1: 30 nm of α-Fe₂O₃ layer was epitaxially grown on an α-Al₂O₃ R-plane (0 1 -1 2) substrate and further covered by 5 nm of Pt, and patterned into Hall bar devices. The magnetic easy plane of α-Fe₂O₃ is the tilted C-plane (0001). Damping-like torque effective fields Hₓ rotate the antiferromagnetic sublattice moments mاحة and mＢ resonate constructively, while the field-like torque Hᵧ does not.
Figure 2: The angle-dependent second-harmonic Hall resistance as a function of field angle $\beta$, at different external fields. The current is 4 mA (root mean square value). $H_{DL}$ (red) and $H_{FL}$ (blue) contributions to second-harmonic resistance at $H = 20$ kOe are separately plotted. $H_{DL}$ corresponds to a damping-like torque efficiency of 0.015, comparable to the value of Pt-ferrimagnetic Insulator bilayers.
Tremendous progress has been made in engineering highly mobile domain walls and skyrmions in room temperature materials for racetrack-based applications. Most recent efforts have focused on heavy-metal/ferromagnet heterostructures with Dzyaloshinskii-Moriya interactions and spin-orbit torques, in which chiral domain walls and skyrmions can be stabilized at room temperature and readily manipulated \cite{1,2}. However, ferromagnets possess fundamental limitations on spin texture speed and size owing to stray fields and precessional dynamics \cite{3}. Antiferromagnets, on the other hand, possess no stray fields, and are angular-momentum-compensated, yielding extremely fast dynamics. Ferrimagnets exhibit similar behaviors at compensation, but are more readily probed since the individually sublattices are detectible and addressable owing to the fact that the electronic and optical properties of the elements on these sites are typically different. Here, I describe ferrimagnetic spin textures and dynamics in metallic and insulating ferrimagnets. Using Pt/GdCo/TaOx films with sizable Dzyaloshinskii-Moriya interaction, we realize current-driven domain wall motion with a speed of 1.3 km/s near the angular momentum compensation temperature ($T_A$) and room-temperature stable skyrmions with minimum diameters close to 10 nm near magnetic compensation ($T_M$) \cite{4}. By using temperature as a knob, the roles of compensation on the dynamics can be clearly extracted. I then describe recent work on insulating magnetic garnets with perpendicular anisotropy, in which we have discovered an interfacial Dzyaloshinskii-Moriya interaction \cite{5,6} which, combined with low damping and pure spin current injection mediated by a Pt overlayer \cite{7}, leads to exceptionally fast motion at extremely low current densities \cite{8}. Finally, I will discuss all-optical manipulation of skyrmions using ultrafast laser excitations, including picosecond generation of topological charge \cite{9} tracked in real time via single-shot soft x-ray scattering. Recent progress and future directions in these areas will be discussed.

References:

\cite{1} S. Emori, et al., Nature Mater. 12, 611 (2013).
\cite{6} L. Caretta, et al., Nat. Comm. 11, 1090 (2020).
\cite{8} L. Caretta, et al., Science 18, 1438 (2020).
\cite{9} F. Buttner, et al., Nat. Mater. 20, 30 (2021).
Reliable and dynamic control of magnetic properties in technologically relevant magnetic materials is at the heart of a variety of emerging practical applications in spintronics. Gate voltage-controlled ionic diffusion in magnetic devices has shown to provide non-volatile control of perpendicular magnetic anisotropy (PMA), the Dzyaloshinskii Moriya interaction (DMI), as well as the velocity and pinning of magnetic domain walls, opening a solid path towards novel multifunctional spintronics devices.

In this talk, I will present a short overview of this exciting field, and discuss the physical mechanisms involved. In this context, I will show our recent results [1-4] on magneto-ionic control of PMA, magnetic domain wall motion and the DMI in a variety of CoFeB/oxide systems. I will show that electric fields induce the migration of mobile oxygen-rich ionic species present in HfO$_2$ across the CoFeB/ HfO$_2$ interface which can define different magneto-ionic regimes in the CoFeB films: under-oxidised (in-plane magnetisation), optimally-oxidised (PMA) and over-oxidised (in-plane magnetisation).

The gate voltage can therefore induce a spin-reorientation transition between magneto-ionic states with in-plane anisotropy and PMA, accompanied by changes in DMI and domain wall velocity.

Our studies show that in Co$_{20}$Fe$_{60}$B$_{20}$/HfO$_2$ stacks the magneto-ionic regime going from under-oxidised to PMA (regime I, see Figure 1) is irreversible at the maximum electric fields allowed in both liquid-gated and solid-state devices and highly reversible and cyclable in the PMA to over-oxidised regime (regime II) at much lower gate voltages. This behaviour is attributed to a non-equivalent distribution and binding of the mobile oxygen species at the surface of the magnetic layer in the different magneto-ionic regimes.

In order to address the dependence of magneto-ionic control of magnetism in CoFeB on the nature of the interfaces and the Co/Fe ratio we also investigated the magneto-ionic response in Co$_{40}$Fe$_{40}$B$_{20}$/MgO/HfO$_2$ and (Y)CoFeB/(X)MgO/HfO$_2$, where Y and X are dusting layers of Pt, W and Ta. In these systems the presence of a CoFeB/MgO interface can highly stabilise PMA, showing a magneto-ionic response limited to the PMA regime, while dusting layers can facilitate the access to regime I. Regime II, accessible in Co$_{20}$Fe$_{60}$B$_{20}$/HfO$_2$, cannot be observed in any of the (Y)Co$_{40}$Fe$_{40}$B$_{20}$(X)/MgO/HfO$_2$ systems, pointing again at the role of the CoFeB/MgO interface in stabilising PMA and the potential influence of the CoFeB composition.

Our studies show the complexity of the magneto-ionic mechanisms and the strong influence of surface chemistry on the observed effects on the magnetic properties. This shows the need to better understand the link between magneto-ionic performance, in terms of the amplitude of the effects on the magnetic properties and their reversibility, and interface composition for the design of efficient spintronics devices with magneto-ionic functionalities.
References:


Figure 1: (left) Graphic representation of the magneto-ionic stack covered with the ionic liquid [EMI][TFSI]− gate. The gate voltage induces the motion of oxygen species in HfO2. (right) A progressive oxidation is induced upon exposure to a gate voltage GV = −2 V. Different exposure times t drive the system from in-plane magnetisation (a, initial state) through regime I (b) into PMA (c) and back to in-plane magnetisation through regime II (d).
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 applications. 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. 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 and (ii) tuning the magnetic properties of wire edges. The possibility to reduce structural defects through He ion irradiation paves the way toward power-efficient memory and neuromorphic devices.
Large Magneto-electric Resistance in the Topological Dirac Semimetal $\alpha$-Sn

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The spin-momentum locking of surface states in topological materials can produce a resistance that scales linearly with both magnetic and electric fields. Such a bilinear magneto-electric resistance (BMER) effect offers a new approach for information reading and field sensing applications, but the effects demonstrated so far are too weak or for low temperatures. This presentation reports the first observation of BMER effects in topological Dirac semimetals; the BMER responses were measured at room temperature and were substantially stronger than those reported previously [1]. The experiments made use of topological Dirac semimetal $\alpha$-Sn thin films grown on silicon substrates by sputtering at temperatures achievable by conventional cooling water. The films showed BMER responses that are 10$^6$ times larger than previously measured at room temperature and are also larger than those previously obtained at low temperatures. These results represent a major advance toward realistic BMER applications. Significantly, the data also yield the first characterization of three-dimensional Fermi-level spin texture of topological surface states in $\alpha$-Sn.

Reference:

https://www.science.org/doi/10.1126/sciadv.abo0052
Stimulate Entrepreneurial Transfer at RWTH Aachen University

U. Ruediger

RWTH Aachen University gains insights into bold scientific questions, transfer forefront knowledge to the next generation of researchers, industry as well as society and develops solutions that impact today’s and future challenges. RWTH’s vision is to further grow beyond a unique integrated, interdisciplinary university by embracing the convergence of knowledge, approaches and insights from the humanities, economics, engineering, natural and life sciences, i.e. biology and medicine.

Entrepreneurial transfer is based on the broad understanding of transfer at RWTH which entails the continuous and mutual exchange of ideas, knowledge, technologies and people within the university, with partner organizations and societal groups as well as industry. The term “entrepreneurial” is not meant in the restricted sense of spin-offs and start-ups only. At RWTH, entrepreneurship refers to a mindset of thinking and acting proactively under uncertainty. With this understanding, the activities focus on developing personal entrepreneurial competencies and providing structural support for entrepreneurial transfer.

Orchestrating entrepreneurship for students and young academics is the overarching goal of the Collective Incubator as part of the Exzellenz Start-up Center.NRW program. As such, this program fuels the RWTH innovation landscape with entrepreneurial spirit and tangible activities. One of the goals of the Collective Incubator is to create a place where students can explore their own innovation capabilities. Based on these support structures more than 100 start-ups found the way to market in 2021.
Spin Torque Switching Dynamics and Mechanisms of Perpendicular Magnetic Tunnel Junctions

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Studying spin-transfer torque switching of perpendicular magnetic tunnel junction free layer is important for technological applications. Moreover, such studies enhance our understanding of the physics of magnetic interactions and dynamics in these systems. Experimental reports indicate a reduced exchange interaction in pMTJ free layers, especially for those including an insertion layer [1]. Here we studied the impact of such reduced interactions on micromagnetics involved during the STT switching of pMTJ free layers [2].

In this talk, I will present our micromagnetic simulation results for STT-switching of pMTJ free layer with reduced exchange interactions: 1) The impact of reduced exchange interaction on switching speed. 2) The effect of inhomogeneous demagnetizing field on switching dynamics. 3) The effect of the current pulse width required for successful switching of pMTJ free layer.

References:

L1₀ -phase FePd Thin Films with Low Damping and High Thermal Stability for High Performance Memory

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Ultrahigh density magnetic memory technologies demand materials possessing bulk magnetocrystalline anisotropy at sub-20 nm lateral sizes for competitive embedded and standalone magnetic random access memory (MRAM) solutions. Several intermetallic structures that order into the L1₀ phase, including Mn-, Co- and Fe-based alloys, present a range of alternatives for MRAM free layer materials with requisite uniaxial perpendicular magnetic anisotropy (PMA) energy density at the MJ/m³ range. Amongst these materials, L1₀ FePd has shown particular promise to realize high-speed and high-density MRAM, due to the large PMA, low Gilbert damping and integrability into complex synthetic ferrimagnetic free layer structures for low-write energy switching.[1, 2]

I will present results on L1₀ phase FePd thin films with low damping and high thermal stability for high performance memory. The FePd films are grown on noble-metal buffer layers (including Ru, Ir, Pt and Rh) deposited on single-crystalline MgO(001) substrates using direct current magnetron sputtering in a custom 13-target ultrahigh vacuum facility (base pressure < 7 x 10⁻⁸ Pa). Temperature-dependent measurements of the perpendicular magnetic anisotropy (PMA) energy and Gilbert damping was evaluated by time-resolved magneto-optic Kerr effect spectroscopy. Our results show that the degree of L1₀ ordering dictates the reduction in PMA field at elevated (150 °C) temperature, with a reduction of nearly 50 per cent in samples with an order parameter of 0.55 but only a reduction of 20 per cent in samples with an order parameter exceeding 0.8. We additionally show that the temperature dependence of the Gilbert damping in these films is most affected by changes in the conductivity of the noble metal buffer layer, through the spin-pumping contribution to the damping. Our advances in understanding the materials and processing of L1₀ FePd will help transition crystalline PMA-based nanomagnets into high-performance memories.

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References:

Neuromorphic Computing

I. K. Schuller

I. K. Schuller

Data manipulation (memory, computation, communications, data mining, sensing) in its many forms drives our modern civilization. The continuous increase in hardware packing density and phenomenal decrease in cost (Moore’s law) has been key to the development of the information revolution. This was fueled by the discovery of revolutionary scientific concepts such as quantum mechanics, coupled with the development of quantum materials and devices. It is however agreed that the enhanced computational capabilities will soon (within the next 5-10 years?) slow down considerably due to a variety of issues which are connected probably to the foundation of the classical Turing-von Neumann paradigm for computing.

At present time, new hardware concepts, based on transformative scientific concepts, are needed. This includes reevaluation of data manipulation concepts for software and systems and by necessity will require development of novel hardware including new device and materials concepts. I will describe some of the first steps by a large group of researchers to implement the grand challenge to “develop a machine that works like the brain”.

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Coherent Sub-terahertz Spin Pumping from an Insulating Antiferromagnet

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Emerging phenomena, such as the spin-Hall effect (SHE), spin pumping, and spin-transfer torque (STT), allow for interconversion between charge and spin currents and the generation of magnetization dynamics that could potentially lead to faster, denser, and more energy efficient, non-volatile memory and logic devices. Present STT-based devices rely on ferromagnetic (FM) materials as their active constituents. However, the flexibility offered by the intrinsic net magnetization and anisotropy for detecting and manipulating the magnetic state of ferromagnets also translates into limitations in terms of density (neighboring elements can couple through stray fields), speed (frequencies are limited to the GHz range), and frequency tunability (external magnetic fields needed). A new direction in the field of spintronics is to employ antiferromagnetic (AF) materials. In contrast to ferromagnets, where magnetic anisotropy dominates spin dynamics, in antiferromagnets spin dynamics are governed by the interatomic exchange interaction energies, which are orders of magnitude larger than the magnetic anisotropy energy, leading to the potential for ultrafast information processing and communication in the THz frequency range, with broadband frequency tunability without the need of external magnetic fields.

I will present the first evidence of sub-terahertz coherent spin pumping at the interface of a uniaxial insulating antiferromagnet MnF₂ and platinum thin films, measured by the ISHE voltage signal arising from spin-charge conversion in the platinum layer. The ISHE signal depends on the chirality of the dynamical modes of the antiferromagnet, which is selectively excited and modulated by the handedness of the circularly polarized sub-THz irradiation (see figure). Contrary to the case of ferromagnets, antiferromagnetic spin pumping exhibits a sign dependence on the chirality of dynamical modes, allowing for the unambiguous distinction between coherent spin pumping and the thermally-driven, chirality-independent spin Seebeck effect. Our results open the door to the controlled generation of coherent pure spin currents with antiferromagnets at unprecedented high frequencies.

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References:
Antiferromagnetic (AFM) materials have ordered spin moments that alternate between individual atomic sites, which gives them a vanishing macroscopic magnetic signature and picosecond intrinsic timescale. Typically, AFM materials are used to exchange bias an adjacent FM layer in spin valves or magnetic tunnel junctions. Recently, it was suggested that spin transfer torque could in principle be used to manipulate the magnetic order in conducting AFMs, leading to either stable AFM order precessions for their use as high-frequency oscillators, or switching of the AFM order for their use as magnetic memories.

In this talk, I’ll present my group’s latest results in the modeling and simulation of the dynamics of the order parameter in metallic non-collinear co-planar AFMs like Mn$_3$Ir and Mn$_3$Sn [1,2]. Physically, these two AFM materials differ in their spin configuration viz. positive chirality for Mn$_3$Ir, and negative chirality for Mn$_3$Sn. The hysteretic dynamics in the case of Mn$_3$Ir allows for possibility to create energy-efficient THz coherent sources. On the other hand, a small threshold current requirement in the case of Mn3Sn indicates the possibility of implementing efficient coherent signal sources from the MHz to the THz regime. Using a circuit model based on the principle of tunnel anisotropy magnetoresistance, we quantify frequency scaling of the output power and the efficiency for both Mn$_3$Ir and Mn$_3$Sn auto-oscillators. We also show that the nonlinear behavior of positive chirality materials with large damping could be used to emulate spiking neurons. An interacting network of such oscillators could enable the development of neurocomputing circuits for various cognitive tasks [3]. I will conclude my talk by summarizing the limits, challenges, and opportunities of antiferromagnetic spintronics for future technologies such as high-density, secure nonvolatile memory, compact narrowband terahertz sources, and spike generators.

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References:

Imaging Ultrafast and Ultrasmall: Unraveling Magnetic and Electronic Behavior Using Time-resolved X-ray Scattering

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Ultrafast laser control of magnetic and correlated materials has emerged as a fascinating avenue of manipulating magnetic and electronic behavior at femtosecond to picosecond timescales. Ultrafast manipulation of these materials has also been envisioned as a new paradigm for next generation memory and data storage devices. Numerous studies have been performed for both magnetic metallic systems as well as complex oxides to understand the mechanism underlying laser excitation. However, it has been recently recognized that spatial domain structure and nanoscale heterogeneities can play a critical role in dictating ultrafast behavior [1-5]. In this talk, I will focus on utilizing time-resolved x-ray scattering and nanodiffraction studies to study spatial texture dependent dynamics in magnetic multilayers and correlated systems. I will describe our recent experimental studies using emerging synchrotron techniques and free electron laser such as European XFEL and FERMI. In magnetic multilayers, we uncover a symmetry-dependent behavior of the ultrafast response. Labyrinth domain structure with no translation symmetry exhibit an ultrafast shift in their isotropic diffraction peak position that indicates their spatial rearrangement. On the other hand, anisotropic domains with translation symmetry do not exhibit any modification of their anisotropic diffraction peak position. Our findings demonstrate that the ultrafast spatial manipulation of the magnetization depends on the pattern’s symmetry. These intriguing observations suggests preferential, texture-dependent paths for the transport of angular momentum and invites further investigation on far-from-equilibrium spin transport. These measurements provide us with a unique way to study and manipulate spin, charge and lattice degrees of freedom.

References:

Inertial Spin Dynamics in Ferromagnets

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The understanding of how spins move and can be manipulated at pico- and femtosecond timescales has implications for ultrafast and energy-efficient data-processing and storage applications. However, the possibility of realizing commercial technologies based on ultrafast spin dynamics has been hampered by our limited knowledge of the physics behind processes on this timescale. Recently, it has been suggested that inertial effects should be considered in the full description of the spin dynamics at these ultrafast timescales, but a clear observation of such effects in ferromagnets has been lacking for about a decade. In this presentation, I will first report on the first direct experimental detection of intrinsic inertial spin dynamics in ferromagnetic thin films, in the form of a forced nutation oscillation of the magnetization at THz frequency, that we observed at the TELBE facility in Dresden, Germany.

Then, I will show our most recent results on the detection of spin nutation using a tabletop broadband THz source, with which we investigated epitaxial thin films of cobalt in its three crystalline phases. The terahertz magnetic field of the radiation generates a torque on the magnetization which causes it to precess for about 1 ps, with a sub-picosecond temporal lag from the driving force. Then, the magnetization undergoes natural damped THz oscillations at a frequency characteristic of the crystalline phase. We describe the experimental observations solving the inertial Landau-Lifshitz-Gilbert equation. Using the results from the relativistic theory of magnetic inertia, we find that the angular momentum relaxation time is the only material parameter needed to describe all the experimental evidence. Our data suggest a proportionality between such time and the strength of the magneto-crystalline anisotropy, deepening our fundamental understanding of magnetic inertia.
In order to develop ultrafast and energy efficient storage devices based on magnetic media, it is usually believed that magnetization must undergo a longitudinal dynamics \([1,2]\) as opposed to a precessional one \([3,4]\). It must then be completely quenched at the sub-picosecond timescale \([5]\) before recovering in the opposite direction. However, when magnetization approaches zero, its dynamics slows down, a phenomenon called Critical Slowing Down (CSD) \([6,7]\) which generally exists when a system is close to a phase transition \([8]\).

In order to explain CSD and explain how it can be avoided in magnetic systems, we introduce a two level mean field model for localized spins (Figure 1) \([9]\). Magnetization dynamics is then understood as transfers of energy and angular momentum, and to each magnetic configuration, one can define a temperature for the spin system even under out of equilibrium conditions. We then show that only angular momentum transfers can lead to magnetization reversal and suppress CSD via two mechanisms referred to as spin heating and spin cooling: the heating and respectively cooling of the magnetic system via exchange of spin with an external bath. These effects are simulated using a s-d model of magnetization dynamics \([10]\), consistent with this framework. Experimentally, we demonstrate the existence of these two mechanisms by monitoring the ultrafast magnetization dynamics of a ferromagnetic \([\text{Co/Pt}]\) multilayer when it is subjected to an external spin current emitted by a GdFeCo alloy \([11]\). We show that magnetization crosses zero in 400 fs and reaches equilibrium in 2 ps. Moreover, using the bipolarity of the source spin current \([12]\), we show that magnetization can be reversed twice consecutively in 650 fs. This shows that one can achieve a complete control of magnetization dynamics at the sub-picosecond timescale, close to the ferromagnetic/paramagnetic phase transition, using ultrashort pulses of spin with tunable polarization.

References:


Two level model of ultrafast magnetization dynamics. A system with magnetization \( m \) formed by localized spins can be represented by the population of its different energy levels. Here the two levels can be populated by up (grey arrows) and down (black arrows) spins (center of the figure). To different populations correspond different energy splittings \( \Delta E = 2mk_BT_C \) in the mean field approach considered. For each magnetization and its corresponding possible configurations, one can associate a spin temperature \( T_S \) (see inset) even in out of equilibrium conditions. Due to the coupling of the (two level) spin system with its external environment, there can be exchange of angular momentum which will either cool down the spin system (remagnetization) or heat it up (demagnetization) depending on the polarization of the transferred angular momentum. The standard way to obtain ultrafast magnetization dynamics is to heat up the system (energy transfer) leading to an ultrafast dissipation of angular momentum. It is not possible to achieve a similarly fast remagnetization in general because cooling of the system relies on heat dissipation via the sample substrate on a much longer timescale, and CSD may happen around \( m = 0 \). Spin cooling and spin heating work analogously but via angular momentum transfer. However, contrary to standard cooling and heating, spin cooling and heating can be achieved interchangeably by changing the sign of the external angular momentum.
Spin Transport in a Conventional Superconductor

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I will give an overview of our work in collaboration with the Department of Materials Science and Metallurgy in Cambridge [1-5] on the spin pumping into a Nb thin film. Unlike conventional spin-singlet Cooper pairs, spin-triplet pairs can carry spin. Triplet supercurrents were discovered in Josephson junctions with metallic ferromagnet spacers, where spin transport can occur only within the ferromagnet and in conjunction with a charge current. Ferromagnetic resonance injects a pure spin current from a precessing ferromagnet into adjacent non-magnetic materials. For spin-singlet pairing, the ferromagnetic resonance spin pumping efficiency decreases below the critical temperature (Tc) of a coupled superconductor. Here we present ferromagnetic resonance experiments in which spin sink layers with strong spin–orbit coupling are added to the superconductor. We show that the induced spin currents, rather than being suppressed, are substantially larger in the superconducting state compared with the normal state and show that this cannot be mediated by quasiparticles and is most likely a triplet pure spin supercurrent. By carrying angular dependence studies of the Gilbert damping we are able to link the generation of a triplet condensate with the Rashba spin-orbit coupling.

References:

Towards Topological Superconductivity in Epitaxial Superconductor-Semiconductor Systems

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A central goal in quantum condensed matter physics is to understand and control the order parameter characterizing the collective state of electrons in quantum heterostructures. For example, new physical behaviors can emerge that are absent in the isolated constituent materials. With regards to superconductivity this has opened new area of investigation in the search for topological superconductivity. This type of superconductivity is expected to host exotic quasi-particle excitations including Majorana bound states which hold promise for fault-tolerant quantum computing. In this talk, we first discuss the important role of epitaxial superconductor-semiconductor hybrid systems as an enabling materials platform. We present unprecedented values of transparency and induced gap that could allow us to reach into previously unexplored parameter regimes. In wide Josephson junctions exposed to magnetic field, we observe a minimum of critical current accompanied with a phase jump in the superconducting phase. We discuss this observation as a signature of a transition between trivial and topological superconductivity. These findings reveal a versatile two-dimensional platform to explore mesoscopic and topological superconductivity for quantum information science.
Simultaneous breaking of inversion and time-reversal symmetries in a conductor yields a non-reciprocal electronic transport, known as the diode or rectification effect, that is, low (ideally zero) conductance in one direction and high (ideally infinite) conductance in the other. Recently several groups have reported a non-reciprocal Josephson Diode effect in which asymmetric critical currents are observed such that a dissipationless supercurrent can flow along one direction but not in the opposite one. We have recently discovered a giant Josephson diode effect in Josephson junctions formed from a type II Dirac semimetal, NiTe$_2$ [1]. A distinguishing feature is that the asymmetry in the critical current depends sensitively on the magnitude and direction of an applied magnetic field and achieves its maximum value when the magnetic field is perpendicular to the current and is of the order of just 10 mT. Moreover, the asymmetry changes sign several times with increasing field. These characteristic features are accounted for by a model based on finite momentum Cooper pairing that largely originates from the Zeeman shift of spin-helical topological surface states.

Indeed, to date, most of the diode effects observed in non-centrosymmetric polar/superconducting conductors and Josephson junctions require external magnetic fields to break the time-reversal symmetry. We have recently reported zero-field polarity-switchable Josephson supercurrent diodes, in which a proximity-magnetized Pt layer by ferrimagnetic insulating Y$_3$Fe$_5$O$_{12}$ serves as the Rashba(-type) Josephson barrier [2]. The zero-field diode efficiency of our proximity-engineered device reaches up to $\pm35\%$ at 2 K, with a clear square-root dependence on temperature. We have demonstrated that exchange spin-splitting and Rashba (-type) spin-orbit coupling at the Pt/Y$_3$Fe$_5$O$_{12}$ interface are key for the zero-field giant rectification efficiency. These developments are highly interesting for future cryogenic memory and logic devices.

References:
