# $4^{th}$ Workshop on
# Spintronic Memory and Logic
# &
# $5^{th}$ Anniversary Symposium
# of
# Fert Beijing Institute

Hosted by: **Beihang University**

May $20^{th}$-$22^{nd}$, 2019

Beijing, China

# Overview

With the end of Moore's law in sight, the semiconductor industry has been in a 'the King is dying' phase owing to the power issue, with many emerging technologies looking to fill the ensuing power vacuum. Spintronics is one such technology and shows great potential in the post-Moore era. Since the discovery of Giant Magneto-Resistance (GMR) effect in 1988, spintronics has achieved a rapid progress and has resulted a significant impact on human lives in the last 31 years. After the first commercialization of spintronics on the read heads of hard-disk-drivers, recent advance has expanded this technology to the whole microelectronics community in terms of sensors, memories, oscillators and processors, as well as to the computer architecture community. A well-known example is the nonvolatile Magnetic Random Access Memory (MRAM), along with various prototypes. Samsung, Globalfoundries, TSMC have announced to start eSTT-MRAM production in 2018.

The "National Plan 111 for foreign experts" project in Beihang University is named "Ultra-low Power Spintronic Memory and Logic". This project aims to solve the high power consumption of the conventional semiconductor integrated circuit technology, through the interdisciplinary study of spintronic materials, devices, circuits, computing systems and architectures to achieve ultra-low power spintronic memory and logic for the future electronics.

This project will focus on new type of spintronic devices such as magnetic tunnel junctions with interfacial perpendicular magnetic anisotropy, electric-field-controlled magnetic anisotropy, interfacial DMI induced skyrmions, spin wave based logic devices, all spin logic, and so on. This project gathers a number of top experts in the world on this research area. We could expect bright prospects based on spintronics.

# Map

**Address:** Beihang University, No.37 Xueyuan Road, Haidian District, Beijing 100191, China

地址：北京市海淀区学院路 37 号北京航空航天大学


★ **1 Metting Room: Second Meeting Room of New Main Building Conference Center**

★ **2 Hotel: Vision Hotel**

# Agenda

## May 19$^{th}$, 2019

## Registration

Venue: **Lobby of Vision Hotel**

Address: Vision Hotel, Beihang University, No.37 Xueyuan Road,

Haidian District, Beijing 100191, China

## May 20th, 2019

| Time | Activities |
|---|---|
| **Opening Ceremony**<br>***Chairman:*** *Prof. Weisheng Zhao, Beihang University* | |
| 09:00-09:20 | **Opening Speech**<br>*Ministry of Science and Technology of PRC* |
| 09:20-09:30 | **Opening Speech**<br>*Prof. Haijun Huang, Vice President of Beihang University* |
| 09:30-09:40 | **Opening Speech**<br>*Prof. Albert Fert, University of Paris-Saclay and Beihang University* |
| 09:40-10:00 | **Progress of 111 Base and Fert Beijing Institute**<br>*Prof. Weisheng Zhao, Beihang University* |
| 10:00-10:20 | **Introduction of MIPT and Exchange Ceremony of MOU**<br>*Prof. Konstantin Zvezdin, Moscow Institute of Physics and Technology* |
| 10:20-11:00 | **Group Photo and Coffee Break** |
| **Chairman**<br>*Prof. Weisheng Zhao, Beihang University* | |
| 11:00-11:40 | **Recent advances on magnetic skyrmions in multilayers**<br>*Prof. Albert Fert, University of Paris-Saclay* |
| 11:40-12:10 | **Recent Progress in Ferri- and Antiferromagnetism**<br>*Prof. Kang L. Wang, University of California, Los Angeles* |
| 12:10-12:40 | **Magnetic Tunneling Junctions Based IoT Data Privacy Protection**<br>*Prof. Ching-Ray Chang, National Taiwan University* |
| 12:40-14:00 | **Lunch**<br>**Venue:** Dining Room, the 3rd Floor, Vision Hotel |

| | |
|---|---|
| **Chairman**<br>*Prof. Yue Zhang, Beihang University*<br>*Prof. Dapeng Zhu, Beihang University* | |
| 14:00-14:30 | **Electrical detection of spin currents generated by magnon-phonon coupling**<br>*Prof. Yoshichika Otani, University of Tokyo* |
| 14:30-15:00 | **Magnetic skyrmions, bimerons and antiskyrmions in new materials**<br>*Prof. Yan Zhou, The Chinese University of Hong Kong* |
| 15:00-15:30 | **Magnetic Domain Wall Devices for Neuromorphic Computing**<br>*Prof. S. N. Piramanayagam, Nanyang Technological University* |
| 15:30-16:00 | **Highly Integrated TMR sensor**<br>*Menghuang Lai, President of iSentek Technology* |
| 16:00-17:30 | **Poster Session and Coffee Break**<br>*Co-chairs: Prof. Shouzhong Peng, Beihang University*<br>*Prof. Xueying Zhang, Beihang University* |
| 18:00-20:30 | **Welcome Dinner** |

## May 21st, 2019

| Time | Activities |
|---|---|
| **Chairman**<br>*Prof. Haiming Yu, Beihang University*<br>*Prof. Lang Zeng, Beihang University* | |
| 09:00-09:30 | **Propagation of domain walls in CoFeB magnetic thin films**<br>*Prof. Nicolas Vernier, University of Paris-Saclay* |
| 09:30-10:00 | **Electric-field control of magnetism in multiferroic heterostructures**<br>*Prof. Yonggang Zhao, Tsinghua University* |
| 10:00-10:30 | **Two-dimensional mutually synchronized spin Hall nano-oscillator arrays for highly coherent microwave signal generation and neuromorphic computing**<br>*Prof. Johan Åkerman, University of Gothenburg* |
| 10:30-11:00 | **Coffee Break** |
| 11:00-11:30 | **Low voltage control of interfacial magnetism in magnetic multilayers**<br>*Prof. Ming Liu, Xi'an Jiaotong University* |
| 11:30-12:00 | **Femto-second light and electron pulses to Switch magnetization**<br>*Prof. Stéphane Mangin, University Lorraine* |
| 12:00-12:30 | **Spintronic realization of recurrent neural networks (RNNs)**<br>*Prof. Ke Xia, Southern University of Science and Technology* |
| 12:30-14:00 | **Lunch**<br>**Venue:** Dining Room, the 3rd Floor, Vision Hotel |

| Chairman<br>*Prof. Na Lei, Beihang University*<br>*Prof. Wang Kang, Beihang University* | |
|---|---|
| 14:00-14:30 | **Introducing Nature Electronics**<br>*Dr. Christiana Varnava, Nature Electronics Editor* |
| 14:30-15:00 | **The novel physical phenomenon in the heterostructures of perovskite nickelate and manganese oxides**<br>*Prof. Xiaohong Xu, Shanxi Normal University* |
| 15:00-15:30 | **Frequency engineering of spin-torque diode**<br>*Prof. Konstantin Zvezdin, Moscow Institute of Physics and Technology* |
| 15:30-15:50 | **Microscopical studies of magnetic dynamics with combined effects of multidimensional magnetic fields and electric current**<br>*Prof. Xueying Zhang, Beihang University* |
| 15:50-16:10 | **A Patterning Solution for Perpendicular STT-MRAM by Utilizing Combined Etching**<br>*Kaidong Xu, President of Leuven Instruments Co. Ltd* |
| 16:10-17:30 | **Poster Session and Coffee Break**<br>*Co-chairs: Prof. Shouzhong Peng, Beihang University*<br>*Prof. Xueying Zhang, Beihang University* |
| 18:00-20:30 | **Banquet Dinner** |

| May 22nd, 2019 | |
|---|---|
| **Time** | **Activities** |
| | **Chairman**<br>*Prof. Qunwen Leng, Beihang University*<br>*Prof. Tianxiao Nie, Beihang University* |
| 09:00-09:30 | **Approach to Ultrafast Spin-Orbit Torque MRAM (SOT-MRAM) & Neural Networks**<br>*Prof. Shanxiang Wang, Stanford University* |
| 09:30-10:00 | **Interplay of chiral energy and chiral dissipation in domain wall dynamics**<br>*Prof. Gilles Gaudin, Spintec* |
| 10:00-10:30 | **High-performance spintronic terahertz generation**<br>*Prof. Tianxiao Nie, Beihang University* |
| 10:30-11:00 | **Coffee Break** |
| 11:00-11:30 | **Is room temperature magnetism possible without d or f electrons?**<br>*Prof. Michael Coey, Trinity College, Dublin* |
| 11:30-12:00 | **Excitation and amplification of coherent spin waves by spin currents**<br>*Prof. Vladislav Demidov, University of Muenster* |
| 12:00-12:30 | **Anomalous Hall and Nernst effects in $Co_2TiSn$ and $Co_2Ti_{0.6}V_{0.4}Sn$ Heusler thin films**<br>*Prof. Haiming Yu, Beihang University* |
| 12:30-14:00 | **Lunch**<br>**Venue:** Dining Room, the 3rd Floor, Vision Hotel |

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|---|---|
| **Chairman**<br>*Prof. Zhaohao Wang, Beihang University*<br>*Prof. Lianggong Wen, Beihang University* | |
| 14:00-14:30 | **Dzyaloshinskii-Moriya Interaction at disordered interfaces in ultra-thin films with Perpendicular anisotropy**<br>*Prof. Dafine Ravelosona, University Paris-Saclay* |
| 14:30-15:00 | **Spin Transport in Antiferromagnetic insulators**<br>*Prof. Zhiyong Qiu, Dalian University of Technology* |
| 15:00-15:30 | **Giant spin-orbit torque in a single ferrimagnetic metal layer**<br>*Prof. Karsten Rode, Trinity College, Dublin* |
| 15:30-16:00 | **Ab-initio antiferromagnetic spintronics:**<br>**from exotic interactions to novel transport effects**<br>*Dr. Jan-Philipp Hanke, Peter Grünberg Institute and Institute for Advanced Simulation* |
| 16:00-16;20 | **Effect of Grain Boundaries in Nanomaterials for Radiation Tolerance**<br>*Prof. You Qiang, University of Idaho* |
| 16:20-16:50 | **Coffee Break** |

## Young Researcher Session

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|---|---|
| **Chairman**<br>*Prof. Xiaoyang Lin, Beihang University*<br>*Prof. Yue Zhang, Beihang University* | |
| 16:50-17:05 | **Study of magnetic skyrmions in Pt/Co/X systems**<br>*Prof. Na Lei, Beihang University* |
| 17:05-17:20 | **Above room temperature topological Hall effect in heavy metal/magnetic insulator heterostructures**<br>*Prof. Qiming Shao, Hong Kong University of Science and Technology* |
| 17:20-17:35 | **Diode assisted magnetoresistance devices for In-Memory Computation**<br>*Prof. Yue Zhang, Beihang University* |
| 17:35-17:50 | **Magnetic modulations in phase change spintronic heterostructures**<br>*Prof. Xiaoyang Lin, Beihang University* |
| 18:00-20:30 | **Farewell Dinner** |

# Abstract

**Recent advances on magnetic skyrmions in multilayers**

Albert Fert

Professor at Université Paris-Saclay (UMP CNRS-Thales, 91767 Palaiseau, France) and Fert Beijing Research Inst., School of Microelectronics, Beihang University, Beijing, 100191, China

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After a general introduction on magnetic skyrmions, I will focus on recent advances in our research on skyrmions induced by interfacial chiral spin interactions in magnetic multilayers based on classical ferromagnetic transition metals (samples fabricated by sputtering and measurements at room temperature):

- creation of skyrmions by current pulses.
- detection of skyrmions by anomalous Hall effect measurements and discussion of the topological Hall effect
- current-induced motion of skyrmions, pinning by defects.
- shaping skyrmions in 3D.
- antiferromagnetic skyrmions in multilayers with antiferromagnetic interlayer couplings.
- skyrmions in the 10 nm diameter range.

I will finally discuss the possible interest of new type of materials, in particular ferromagnetic metals of large spin-orbit coupling and 2D materials.

**Recent Progress in Ferri- and Antiferromagnetism**

Kang L. Wang

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Energy dissipation has become a major challenge for today's electronics. With nonvolatile magnetic memory, logic and alike, leakage current may be minimized and the voltage scaling may be further advanced. Recent advances in the physics of spintronics have made spin-transfer torque, spin-orbit torque and voltage controlled magnetic memory devices possible. The operation speed of these above devices is limited by the ferromagnetic resonance frequency. Antiferromagnetic (AFM) and ferri-magnetic materials (FRM) offer the speed advantage to THz and in particular, insulating materials provide an additional advantage of low energy operation, allowing for information propagation in the form of spin waves, i.e., magnons, like magnetic metals but without electrical charge current loss. First, I will discuss some of the recent progress and results. A topological insulator/AFM (MnTe) heterostructure will be described to show the use of the induced exchange bias via interface proximity effect to control the topological charge number via field cooling. Then, we will discuss the exchange coupling of the two sub-lattices of FRM and AFM, in particular, the heavy metal/TmIG bilayer as probed by XMCD (X-ray magnetic circular dichroism), neutron scattering, and anomalous Hall effect. The temperature and layer thickness dependences show the dominant exchange coupling of the Fe sublattice. Spin-orbit torque and switching of FRM will be illustrated in both Bi2Se3/GdFeCo and Pt/TmIG structures, showing the much-improved energy. Insulating AFM and FRM spin-orbit torques offer advantageous spintronics devices. Likewise, the AFM and FRM Skyrmions offer the potential of using Skyrmions for low energy dissipation systems.

*The work was in part supported by ERFC-SHINES, MURI-ARO, TANMS, and NSF.

**Magnetic Tunneling Junctions Based IoT Data Privacy Protection**

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The rapid development of microelectronics industry and spintronics has revolutionized capabilities of Internet of Things (IoT). However, one of the major problems of IoT is that the limitation of the currently available technology cannot simultaneously provided the solution of lower power consumption, high endurance, high security and non-volatile in data process which are critical for IoT application designing. Spin torque transfer magnetic random access memory (STT-MRAM), in addition to a lower power consumption and high endurance in data process, can also use as embedded non-volatile memory in IoT devices. However, security for data and hardware still reserves a tremendous challenge in IoT applications. Motivated by this, we investigate spintronics and propose magnetic tunneling junction (MTJ) based data privacy protection mechanism for data collection from IoT devices equipped with STT-MRAM while satisfying rigorous data privacy guarantee. Analyzing the collected data, we can detect malware activities in IoT devices to achieve the goal of hardware security protection. More precisely, MTJ can generate random events by controlling input voltage and be a hardware random number generator in our system. According to unpredictable period of hardware random numbers, a novel data randomized encoding approach is designed to guarantee data privacy while preserving the feature of population statistics. Through well-designed randomized encoding and the corresponding decoding algorithms in IoT devices equipped with STT-MRAM, our system can not only have rigorous data privacy guarantee but also perform exceptionally in terms of efficient and high-utility malicious behaviors analysis for the collected population of data in protecting hardware security.

**Electrical detection of spin currents generated by magnon-phonon coupling**

YoshiChika Otani

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Spin conversion, the key concept of Spintronics, has been vigorously investigated in order to gain deeper understanding of spin dynamics and enriching the functionalities of electronic devices. It describes various intriguing phenomena taking place at the nanoscale between electricity, light, sound, vibration, heat and etc., based on the interconversions mediated by spin [1]. However, among the above, the interaction between spin and sound-vibration prevails not well explored.

In the presence of magnetic materials, mechanical oscillation energy can be transferred to spin via magnon-phonon coupling. When surface acoustic waves (SAWs) are passing across ferromagnetic layers, periodic elastic deformation induced by SAWs drives precession magnetization dynamics, well known as acoustic ferromagnetic resonance (A-FMR) [2], generating spin current flow into adjacent nonmagnetic layers (see Figure 1.).

The generated spin current is usually converted to electrical charge current by inverse spin Hall effect (ISHE). Alternatively, recent reports showed efficient spin to charge current conversion at interfaces with spatial inversion asymmetry between two nonmagnetic materials [3, 4]. Spatial inversion asymmetry induces a built-in electric potential and spin orbit coupling at surfaces and interfaces, the so-called Rashba spin orbit coupling. Here, the spin to charge conversion mechanism is known as inverse Edelstein effect (IEE) [5]. In this talk, we discuss the spin to charge conversion in a hybrid device which combines magnon-phonon coupling via SAWs and inverse Edelstein effect (IEE) [6].

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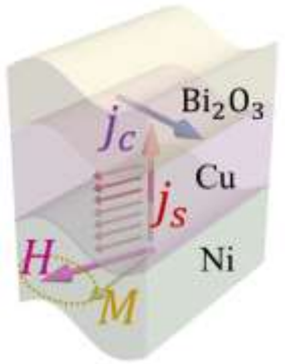

Figure 1. Schematic illustration of acoustic spin pumping (ASP)

**Magnetic skyrmions, bimerons and antiskyrmions in new materials**

Yan Zhou

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In this talk, Dr. Yan Zhou will discuss his recent work of magnetic skyrmions, bimerons and antiskyrmion in new material systems, i.e., antiferromagnets, ferrimagnet and frustrated magnets [Nature Electronics, 1, 288-296, (2018); Nature Communications, 9, 959, (2018); Nature Physics, 13, 162–1169 (2017); Nature Communications, 8, 1717, (2017); Nature Communications, 7, 10293 (2016)]. It is shown that the skyrmion Hall effect can be partially or completely suppressed in ferri-, antiferro- or frustrated materials in comparison to ferromagentic materials, making magnetic skyrmions in the new systems suitable for memory applications. In addition, he will discuss many novel physics of these intriguing topological spin textures in the new materials systems and highlight their potential device applications.

# Magnetic Domain Wall Devices for Neuromorphic Computing

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Due to the emergence of Artificial Intelligence and the need to go "Beyond Moore", the electronics industry is looking at neuromorphic computing as a potential alternative. In neuromorphic computing, the computer architecture is wired similar to the human brain and the computing elements work similar to the way neurons and synapses function. However, achieving neuromprhic computing elements require significant amount of research. Resisitive RAM has been considered as a potential candidate for synapse. Whereas, spin-based devices can function both as neurons and synapse. In this connection, domain wall memory devices play an important role.

One of the challenges of domain wall memory devices is the control of domain wall motion. We have been carrying out research on pinning the domain walls in materials with in-plane magnetization and materials with perpendicular magnetic anisotropy. For materials with in-plane magnetization, elemental diffusion and other methods have shown fruitful results. For materials with out-of-plane magnetization, ion-implantation at selected regions has been shown to be useful. Several new methods are also being investigated.

In this talk, I will present an overview of various domain wall pinning methods. Then, some of the preliminary results that we have achieved that would lead towards making synaptic devices and neurons based on domain wall memory will be discussed. I will highlight some of the experimental investigations and advances that we have made in Co/Pd multilayers based nanowires in connection with neuromorphic computing.

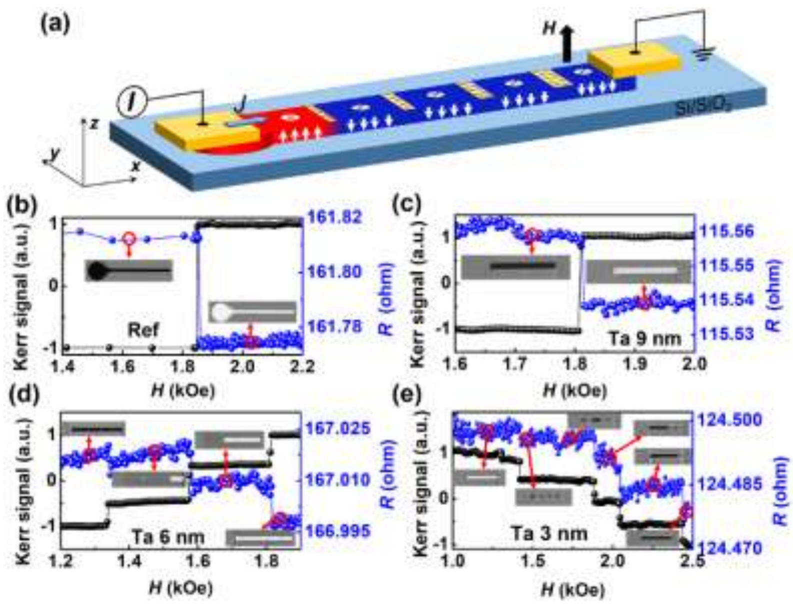


Figure 1. Magnetic domain wall devices based on Co/Pd multilayers

## Highly Integrated TMR Magnetic sensors

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Driven by the rapid development of modern technology, magnetic-based sensing plays a crucial role in these technologies, such as heading information for the navigation, angle sensing, current sensing and leakage sensing for the electric vehicle and smart grid. Advanced application requires high sensitivity, wide dynamic range, low power consumption, high temperature stability and compact size. Conventionally, the TMR sensor has been made by the multiple chips design, even for the single sensing direction, as there are multiple pining directions. This makes the compact size and the orthogonality become very challenging. iSentek has the core technologies to build full Wheatstone bridge with integrating TMR elements into one chip. We can integrate multiple directional pinned TMR element into one chip or using single pining direction TMR element to build full Wheatstone bridges for multiple direction sensing. The core technologies solve the traditional challenges of TMR, which will make it ubiquitous for the coming advanced applications.

**Two-dimensional mutually synchronized spin Hall nano-oscillator arrays for highly coherent microwave signal generation and neuromorphic computing**

Johan Åkerman

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Mutually synchronized spin torque nano-oscillators (STNOs) are one of the promising platforms for bioinspired computing and microwave signal generation [1,2]. Using STNOs one can achieve 90% recognition rate in spoken vowels [3]. However, in order to do more complex tasks, larger scale synchronized oscillators are needed, something that is not easily done with the STNOs demonstrated so far.

In my talk, I will describe a different type of spin current driven device called spin Hall nano-oscillators (SHNOs), which can generate microwave frequencies over a very wide frequency range [4]. The SHNOs are based on 50 – 120 nm wide nano-constrictions in Pt(5)/Hf(0.5)/NiFe(3) trilayers (all numbers in nm). When multiple nano-constrictions are fabricated close to each other (300 – 1200 nm separation) they can mutually synchronize and chains of up to nine nano-constrictions have been demonstrated to exhibit complete synchronization [5]. For the first time, we can now also synchronize two-dimensional SHNO arrays with as many as 8 x 8 = 64 SHNOs [6]. The mutual synchronization is observed both electrically and using scanning micro-BLS microscopy. Both the output power and linewidth of the microwave signal improves substantially with increasing number of mutually synchronized SHNOs, such that quality factors of about 170,000 can be reached. Following the approach of Romera et al [3], we also demonstrate neuromorphic computing using a 4 x 4 SHNO array with two injected microwave signals as inputs. Given their high operating frequency (~10 GHz), easy of fabrication, and highly robust synchronization properties, nano-constriction SHNO arrays are likely the most promising candidates for neuromorphic computing based on oscillator networks.

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## Electric-field control of magnetism in multiferroic heterostructures

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With the fast development of information storage, exploiting new concepts for dense, fast, and non-volatile random access memory with reduced energy consumption is a significant and challenging task. To realize this goal, electric-field control of magnetism is crucial. In this regard, multiferroic materials are important and have attracted much attention due to their interesting new physics and potentials for exploring novel multifunctional devices [1, 2]. In the multiferroic materials, electric polarization can be tuned by applying an external magnetic field or vice versa. This magnetoelectric (ME) effect originates from the coupling of the magnetic and ferroelectric orders. However, single-phase multiferroic materials are rare and the multiferroic heterostructures, composed of ferromagnetic (FM) and ferroelectric (FE) materials, provide an alternative way for exploring the ME coupling effect. One of the key issues in the study of the FM/FE heterostructures is the control of magnetism via electric fields, which is essential for the new generation information storage technology. We have combined ferroelectric $Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O_3$ (PMNT) with different materials and studied the electric-field control of magnetic and electronic transport properties of thin films and magnetic tunnel junctions grown on PMNT [3]. In this talk, I'll present our recent progress in electric-field control of magnetism in magnetic thin films, multilayers, magnetic tunnel junctions and small islands grown on PMNT, involving some interesting behaviors as revealed by both macroscopic and spatially-resolved techniques [4], for example, the giant nonvolatile manipulation of magnetoresistance in magnetic tunnel junctions by electric fields via magnetoelectric coupling. Our work demonstrates the interesting new physics and potential applications of electric-field control of magnetism in multiferroic heterostructures.

References

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**Propagation of domain walls in CoFeB magnetic thin films**

Nicolas VERNIER[1], Xueying ZHANG[1,2], Xiaochao ZHOU[1,3], Berthold OCKERT[4], Sylvain EIMER[1], Laurent VILA[5], Guillaume AGNUS[1], Ya ZHAI[3], Dafiné RAVELOSONA[1] and Weisheng ZHAO[2]

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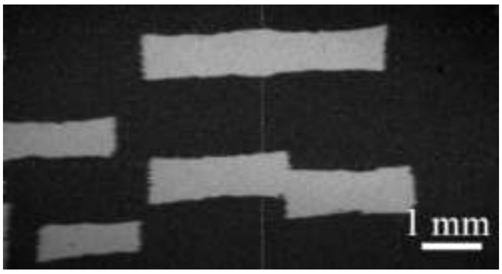
Some theories for the propagation of magnetic domain walls assume perfect materials, without any defect. However, real materials are not perfect. In magnetic thin films, there are plenty of pinning defects, which induce behaviours completely different than the ones predicted in perfect samples. With CoFeB, it has been possible to make very soft magnetic thin films, which can be hoped to be a model system to check theories for perfect materials. We present here several experiments carried in this kind of magnetic thin films, and we compare the results to the prediction of perfect materials theories.

To begin with, we have studied very thin CoFeB thin films with out-of-plane anisotropy. With magnetic induced propagation, the behaviour predicted by Walker cannot be seen, the quantity and the strength of the pinning defects seems to be still too high. However, in CoFeB nanowires, using both magnetic field and spin polarized current simultaneously, we could see a behaviour in agreement with the prediction of the 1D model. From this, we have been able to deduce a spin polarization of the charge carriers in our wires : we have found a quite low value, much lower than previously reported results. One possible explanation is the effect of the metallic layer on which the CoFeB was deposited.

To check this effect, we have started to study thicker films of CoFeB, so that the effect of the buffer layers would become negligible. However, by increasing the thickness, due to the shape energy contribution, the anisotropy turns in-plane. So, the first step has been to check domain walls propagation in this kind of sample. Indeed, in in-plane 2D films, there is almost no experimental result about 2D propagation. We have been able to create very short in-plane magnetic pulses for our purpose, and we have obtained challenging results : when the magnetic is applied along the easy direction axis, the nature of the domains created by the pulses were rectangles, with zig-zag structures on two sides. Furthermore, the propagation was highly anisotropic. Some of these unexpected features can be explained in a quite straightforward way, but, analysis is still on progress to fully understand everything.




*Domain structure obtained after saturation in one direction, followed by nucleation and propagation induced by two magnetic pulses of amplitude 1.56mT and duration 1.0µs.*

**Femto-second light and electron pulses to switch magnetization**

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Since the first observation of magnetization switching in ferrimagnetic GdFeCo alloy films using femtosecond laser pulses in 2007 [1], understanding the mechanism behind all-optical switching (AOS) is becoming a topic of huge interest in the magnetism community. Moreover ultrafast magnetization switching in magnetic material thin film without any applied external magnetic field is drawing a lot of attention for the development of future ultrafast and energy efficient magnetic data storage and memories.

Two type of all optical switching have then ben distinguished: Helicity Independent – All Optical Switching (HI- AOS) and Helicity Dependent – All Optical Switching (HD- AOS). HI-AOS has only been demonstrated for GdFeCo based material and is observed after a *single* laser pulse [2]. After one pulse the magnetization is reversed in the opposite direction independently of the light helicity. On the other hand, HD- AOS has been observed for a large variety of magnetic material such as ferrimagnetic alloy, ferrimagnetic multilayer, ferromagnet, and granular media [3-5]. However several studies shows that HD-AOS is only observed after multiple pulses [6]

During the presentation I will present experimental results showing that the number of pulses can be reduced significantly in order to switch ferromagnetic [Co/Pt] multilayers using only several light pulses. Those results can be explained by considering the transfer of heat and angular from light to the sample's electron bath [7]

In all the previously reported experiments light is used to manipulate magnetization. However, recently we have engineered multilayer structures in order to create hot electrons femto second pulses. We have demonstrate that the magnetization of GdFeCo can be switched using a femto-second hot electron pulse with no direct light interaction [8] which confirm the work from Wilson *et al* [9]. Indeed they reported the switching of GdFeCo/Au bilayer via hot electrons generated by single pulse femtosecond laser. Moreover we have studied the magnetization reversal in a GdFeCo / Cu / [Co/Pt] spin valve structure. We observed single shot switching of both the ferrimagnetic GdFeCo and the ferromagnetic [Co/Pt] layer. The magnetisation switching is found to be mediated by spin polarized hot electron transport [10].

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## Low voltage control of interfacial magnetism in magnetic multilayers

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One of the central challenges in realizing magnetoelectric (ME) devices lies in finding a deterministic way to modulate magnetism in integrated circuits with a circuit-operation voltage. Ionic liquid (IL) gating on magnetic thin films with abundant electronic, chemical and magnetic interactions at the interface has become an emerging technology for controlling magnetism in a fast, compact and energy-efficient way. Compared with conventional strain effect dominated piezo/ferroelectric layer multiferroics, IL gating method has advantages like small gating voltage ($V_g$<5 V), easy-to-integration and compatibility with varied substrates such as Si, flexible substrates etc. In additional, unlike the oxide structures require a high temperature to overcome the oxidation energy barrier, the IL gating control process can be operated at room temperature, suitable for applications in room temperature environment. Here, we will summarize our recent progresses of IL gating control of magnetism in varied magnetic heterostructures, as well as in different manners.[1-5] As IL gating process, proven to be a truly powerful and compatible gating method, enables giant ME tunability in different heterostructures and provides a tremendous potential in next generation of voltage-tunable spintronics/electronics.

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**Spintronic realization of recurrent neural networks (RNNs)**

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In the past decade, significant progress has been made in artificial Intelligence, where advanced algorithms using artificial neural networks (ANNs) have been successfully applied in many areas. There have been many attempts to design and fabricate neuromorphic hardware devices, which are not limited by the von Neumann bottleneck and intrinsically possess all the aforementioned advantages. In this talk, we will report a theoretical realization of RNNs with magnetic tunnel junctions, which are used as the basic units of spin-transfer-torque magnetic random access memory. By performing a micromagnetic simulation, we demonstrate that an RNN consisting of as few as 40 MTJs can generate and recognize sequential signals after an efficient training process. The capability of the network can be significantly improved by increasing the number of MTJs.

## **Introducing Nature Electronics**

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Launched in January 2018, *Nature Electronics* is an online-only monthly journal publishing the best research from all areas of electronics, incorporating the work of scientists, engineers and researchers in industry. *Nature Electronics* publishes both fundamental and applied research across all areas of electronics, from the study of novel phenomena and devices, to the design, construction and wider application of electronic circuits. It also covers commercial and industrial aspects of electronics research. The journal focuses on the development of technology and on understanding the impact such developments could have on society. In this talk I will introduce the journal and try to answer any questions you have about getting published. I'll also cover: what we look for in the papers that we consider for publication; the mechanics of how submissions are handled; how to decide if your paper could be for us; and what to do when you think we (or our referees) have got a decision wrong.

## The emergent phenomena in the perovskite nickelates and manganites heterostructures

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Transition metal oxides have attracted a lot of attetions in condensed matter physics and material science over the last two decades. This is due to the strong correlation effects result in many novel physical properties, such as, high-temperature superconductivity, magnetoresistance, multiferroic, and metal-to-insulator transition [1]. The significant characteristics of perovskite rare-earth nickelates (except for $LaNiO_3$) are the sharp metal-to-insulator transition and the irregular antiferromagnetism state as the temperature decrease. The electrical transport behavior of nickelates is insulator-to-metal transition as the temperature increase rather than metal-to-insulator transition in manganites. Therefore, the perovskite nickelates are typical Mott insulator materials [2]. Moreover, the least distorted member of the nickelate family, $LaNiO_3$, is an exception since it only exhibits metallic paramagnetic behavior over all temperatures [3]. Perovskite manganites also have much of abundant physical properties, such as, charge-spin-orbital order, metal-to-insulator transition, phase separation, and giant magnetoresistance effect. Thus, the high-quality heterostructures composed of these two materials have been grown in our group. The emergent phonomena, such as, insulator-to-metal transition, robust exchange coupling effect and superconductivity properties, have been observed in these heterostructures. Furthermore, the internal mechanisms of these novel phenomena also have been revealed by our experimental designs. Our findings will provide important foundation for the research of perovskite nickelate-based heterostructures.

Keyword: Nickelates, Manganites, Heterostructures, Exchange coupling effect, Metal-to-insulator transition

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**Frequency engineering of spin-torque diode**

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One of the emerging novel spintronic technologies is a spintorque diode. Based on the radiofrequency rectification phenomenon (so called spintorque diode effect), it could be used for detecting radiofrequency signals and microwave energy harvesting, as its sensitivity significantly overcomes sensitivity of commonly used Schottky diodes. For implementing this technology into a working prototype, we present several configurations of spin-torque diode, considered by micromagnetic modeling, aiming at achieving high sensitivity, comparable to the one of Schottky diode, in a wide range of frequencies. The first concept includes a spin-torque diode with both magnetic layers softly pinned at some tilt to each other using antiferromagnets with different Neel temperature. The resonance operating frequency of such dual exchange pinned spin-torque diode can be significantly higher (up to 9.5 GHz) than that of a traditional free layer spin-torque diode. At the same time, it is possible to tune the frequency of such diode during the manufacturing by choosing the angle between the pinning fields. The second concept is a vortex spin-torque diode, represented by MTJ with tilted polarizer and vortex magnetization distribution in the free layer. In this case the resonant frequency can be moved down to 300-400 MHz. For both cases the impacts of the bias current are considered.

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## Microscopical studies of magnetic dynamics with combined effects of multidimensional magnetic fields and electric current

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Studies of magnetic dynamics, including magnetic domain wall (DW) motions, are interesting for the development of novel spintronic devices, for the characterization of properties of magnetic materials and for the understanding of underlying physics. Kerr microscopy is an effective method to performs these studies. In this talk, we present several recent research results on the spin dynamics under the combined effect of various stimulation conditions via multifunctional Kerr microscopes. First, using the coordinated work of fast magnetic field pulses and a permeant magnetic field, we have nucleated micron-size domain bubbles and have directly observed their spontaneous deflation induced by the effect of domain wall (DW) surface tension [1–3]; Second, using the combined effect of in-plane and the perpendicular magnetic field, the strength of Dzyaloshinskii-Moriya interactions can be quantified by observing the asymmetrical expansion of magnetic bubble. Based on this method, we find that changing the thickness of MgO layer can be an effective method to tune the strength of DMI in Pt/Co/MgO/Pt film [4]; Third, using the combined effect of in-plane magnetic field and electric current, we have observed the ultra-efficient spin-orbit torque induced magnetic switching in a W/CoFeB/MgO Hall bar structure [5]. This high efficiency is explained by the large spin Hall angle of W and low pinning effect of CoFeB alloy. At last, a multifunctional Kerr microscope designed and realized by the Qingdao research institute will be presented.

We believe the above research results are interesting for the development of novel spintronics devices based on the combined effect of various stimulations.

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## A Patterning Solution for Perpendicular STT-MRAM by Utilizing Combined Etching

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### Biography

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### Abstract

In recent years, the booming of information has promoted the development of high speed and low power consumptive memories for electronic apparatuses. However, conventional memories, such as dynamic random-access memory (DRAM) and flash memory, is confronted by various limitations which influence further applications as memory devices. Therefore, varieties of new memory devices are actively investigated to solve this problem. Among them, spin transfer torque magnetic random access memory (STT-MRAM) has received a lot of attention because of its high-speed operation, non-volatility, almost infinite endurance and low power consumption.

In STT-MRAM device, the magnetic tunnel junction (MTJ), which is composed with ferromagnetic layer, dielectric tunneling barrier layer and ferromagnetic layer, is the critical factor for performance. In order to obtain good performance STT-MRAM with small scale, processing MTJ stacks requires specially developed nano-patterning solution. However, it is still very much a laborious process for STT-MRAM to replace conventional memories. Because MTJ stack materials, such as CoPt and CoFe, cannot easily form volatile compounds at low substrate temperatures by conventional halogen-based etch process, corrosion tends to occur during the etching. Recent studies have focused on traditional reactive ion etching (RIE) processes that employ non corrosive gas, such as CO, $NH_3$, $CH_3OH$, Ar, $CH_4$ and $CO_2$. But there are still problems when patterning MTJ cells, such as low etch selectivity with hard mask, etch damage, poor MTJ profile and re-deposition of etch residues on sidewalls. Therefore, improved methods and apparatus for fabricating MTJ structures are urgently needed for STT-MRAM applications.

Currently, several methods have been attempted to achieve MTJ stack with high performance. One is the ion beam assisted organic chemical vapor etch process. The etch rate of magnetic metals was enhanced. But the formation of organometallic compounds is challenging due to the low reactivity between organic ligands and metals. Pulse-biased inductively coupled plasma (ICP) technique is another method to increase

the formation of volatile and stable metal carbonyl compounds between MTJ materials and etch gas. Controlling the pulse duty ratio can decrease the surface roughness and residual thickness of the etched MTJ. But the non-volatile etch residue remained on the sidewall, resulting in a decrease performance. Also, some researchers used RIE process over ion beam etching (IBE) process gave better sidewall re-deposition and sidewall damage. However, the profile needs to be improved as the scale down to sub 30 nm.

In this paper, we combine ICP etch and IBE process together for the patterning of perpendicular MTJ stacks. ICP offers high plasma density and high etch rates. ICP allows the fast definition of the required patterning profile at small CD and relatively large aspect ratio. IBE offers damage-free remote plasma with noble gasses. An IBE etch and post-etch process is utilized to control the sidewall re-deposition and the sidewall damage. Furthermore, an in-situ deposition of dielectric layer protects the MTJ cells prior to the exposure of MTJ to the ambient. By using a proper hard mask strategy, a new patterning apparatus and a new patterning approach is introduced, which is believe to be the patterning vehicle for STT-MRAM for DRAM replacement applications.

***Keywords—Magnetic random access memory (MRAM); Multiple-tunnel junction (MTJ); Inductively coupled plasma (ICP); Dry etch; In-situ deposition***

**Approach to Ultrafast Spin-Orbit Torque MRAM (SOT-MRAM) & Neural Networks**

Shanxiang Wang, Stanford University

**Abstract:**

The scaling down of semiconductor devices has been improving the speed of computing, which in turn has been increasing power consumption. A possible solution to limit power consumption is normally-off computing in which on-chip volatile memories are replaced with non-volatile memories. In-memory computing and stochastic neutral networks based on ultrafast MRAM also promise to greatly boost the capability of machine learning and AI.

For ultrafast and energy efficient MRAM and AI, a writing speed of < 1 ns is desired to keep up with the speed of CPU. Spin-orbit torque (SOT) effect is capable of magnetization switching in sub-ns regime. However, all the SOT-MRAM studied so far have a three-terminal structure because an in-plane current is required. This increases the cell size due to the requirement of two isolated contacts with associated interconnects. We have demonstrated an experimental two-terminal SOT-MTJ device with great promises of ultrafast switching and smaller cell sizes. We confirmed that the switching is dominantly caused by the SOT effect rather than the conventional spin-transfer torque effect. However, the thickness control and patterning of ultrathin heavy metal SOT layer remains a challenge. In other veins, Voltage Control Magnetic Anisotropy (VCMA) materials and novel topological materials with large spin-Hall angles are expected to further improve the density and speed of SOT-MRAM. Taken together, we are working towards a hybrid three-terminal SOT-MTJ device in which in-plane current and out-of-plane current (or voltage) are simultaneously generated. A large array of such devices are very attractive for ultrafast MRAM and stochastic neural network applications.

**Speaker Biography:**

Dr. Wang is the Leland T. Edwards Professor in the School of Engineering, Stanford University. He is a Professor and Associate Chair of Materials Science & Engineering and jointly a Professor of Electrical Engineering, and by courtesy, a Professor of Radiology (Stanford School of Medicine). He directs the Center for Magnetic Nanotechnology and is a leading expert in biosensors, information storage and spintronics. His research and inventions span across a variety of areas including magnetic biochips, in vitro diagnostics, cancer biomarkers, magnetic nanoparticles, magnetic sensors, magnetoresistive random access memory, and magnetic integrated inductors. He was named an inaugural Fred Terman Fellow, and was elected a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) and a Fellow of American Physical Society (APS) for his seminal contributions to magnetic materials and nanosensors. His team won the Grand Challenge Exploration Award from Gates Foundation (2010), the XCHALLENGE Distinguished Award (2014), and the Bold Epic Innovator Award from the XPRIZE Foundation (2017).

## Interplay of chiral energy and chiral dissipation in domain wall dynamics

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The structural inversion asymmetry gives rise to a chiral energy term as well as a chiral damping mechanism. While the former is well known (arising from the Dzyaloshinskii–Moriya interaction – DMI), the latter was recently evidenced by measuring the field-driven domain-wall (DW) motion in perpendicularly magnetized asymmetric Pt/Co/Pt trilayers [1]. The DW dynamics associated with the chiral damping and those with DMI exhibit identical spatial symmetry. However, they are differentiated by their time reversal properties: whereas DMI is a conservative effect that can be modeled by an effective field, the chiral damping is purely dissipative and has no influence on the equilibrium magnetic texture. We investigate the qualitative and quantitative differences between these two phenomena, and evidence their coexistence and interplay in field and current induced DW dynamics.

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**Is room temperature magnetism possible without d or f electrons?**

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There are numerous reports of 'ferromagnetic-like' magnetization curves originating from materials that do not possess the d or f electrons that are normally associated with ferromagnetic order. The data are characterized by an absence of the temperature dependence and coercivity that generally accompany magnetic order. The saturation magnetization may be orders of magnitude less than the extrapolated saturation field. Progress towards understanding the phenomenon is important in the context of oxide spintronics, and it hinges on finding out what promotes/destroys the effect. Three oxide examples are presented: CeO2 nanoparticles (La-doping/nanoparticle separation); SrTiO3 surfaces (reduction or pulverization/tiron surface treatment); nanoporous amprphous alumina (pore area/salycylic acid treatment), The data establish that surface defects are responsible. Two explanations are considered

1) a spin-split ferromagnetic defect-related impurity band and

2) giant orbital paramagnetism due to coherent electronic state associated with zero-point fluctuations of the vacuum electromagnetic field.

The second seems to be more likely. it important to be aware of the effect when measuring the magnetism of thin film stacks deposited on SrTiO3

## Excitation and amplification of coherent spin waves by spin currents

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Downscaling poses a number of new challenges for the implementation of magnonic devices utilizing spin waves as nano-scale information carrier. In particular, the traditional inductive method for spin wave excitation becomes inefficient at nanoscale. An alternative approach to the excitation of spin waves can utilize the spin-transfer torque generated by pure spin currents, which provide the opportunity to utilize low-damping insulating magnetic materials and to compensate the spin-wave damping over extended areas.

In this talk, I review our recent experiments on utilization of pure spin currents created by the spin-Hall effect and the nonlocal spin injection for excitation and manipulation of coherent propagating spin waves in magnonic nano-structures based on metallic and insulating magnetic films. I show that spin currents enable novel functionalities of magnonic devices not achievable by using traditional approaches. In particular, spin currents allow highly efficient excitation of continuous spin waves and short spin-wave packets with the duration down to a few nanoseconds. These demonstrations open a route for implementation of high-speed magnonic devices characterized by high information flow capacity.

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**Anomalous Hall and Nernst effects in $Co_2TiSn$ and $Co_2Ti_{0.6}V_{0.4}Sn$ Heusler thin films**

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The field of spintronics has been constantly searching for materials with large spin polarizations. The cobalt-based Heusler alloys are coming under intense scrutiny due to the promising applications in ultralow-energy spintronics, for their high spin polarization and half-metallic electronic structure. This study uses epitaxially grown magnetic Heusler compounds $Co_2TiSn$ (CTS) and vanadium doped $Co_2Ti_{0.6}V_{0.4}Sn$ (CTVS) thin films to investigate the Magnetotransport (magnetoresistance and anomalous Hall effect) and thermoelectric (Seebeck and anomalous Nernst effect) effects. Along the way, by using the Mott formula, we deduced the anomalous Nernst angle in analogy to the anomalous Hall angle, and the anomalous Nernst angle for CTVS is 15% at 220 K, whereas it is only 0.5% for the undoped film at 300 K. The intuitive comparison of the experimental results is shown in Fig. 1 and the relation between these two angles has been revealed. Considering the Mott relation, these experimental results may be accounted for by an enhanced energy derivative of the anomalous Hall conductivity at the Fermi level that is shifted by vanadium doping. This insight might provide opportunities to realize spin caloritronic devices for efficient on-chip energy harvesting based on magnetic Heusler thin films.

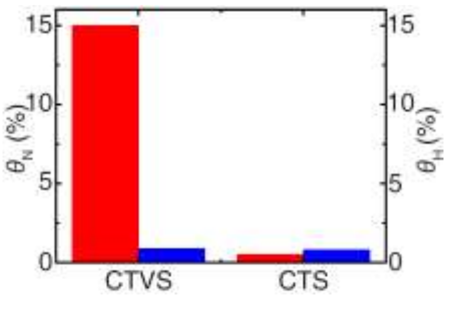


Fig.1. Anomalous Nernst angles (red column) and anomalous Hall angles (blue column) of the CTVS and CTS samples. The results are measured at 220 K for CTVS, at 300 K for CTS.

**Dzyaloshinskii-Moriya Interaction at disordered interfaces in ultra-thin films with Perpendicular anisotropy**

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Study of domain wall (DW) dynamics in perpendicular magnetic anisotropy (PMA) materials is of great interest due to its potential for applications in memory, logic and sensing devices. In particular, the presence of Dzyaloshinskii-Moriya Interaction (DMI) at interfaces of a ferromagnetic metal and heavy non-magnetic metal has been recently recognized to play a crucial role in enabling fast chiral domain wall dynamics driven by spin-orbit torques (SOT).

Here, we have used interface engineering to manipulate domain wall dynamics in (W or Ta)/CoFeB/MgO and Pt/Co/HfO2 structures with PMA and DMI. Interface engineering has been performed using two different approaches: (i) ion irradiation induced interface intermixing and (ii) electric field effect through the oxide layer. We will show that depending on the heavy metal and the oxide in contact with the ferromagnetic layer, the effect of interface disorder and electric field on both DW dynamics and DMI can be radically different.

## Spin Transport in Antiferromagnetic insulators

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Electrical spin - the key element of spintronics - has been regarded as a powerful substitution for the electrical charge in the next generation of information technology, in which spin plays the carrier of information and/or energy as the electrical charge did in electronics. Spin transport phenomena in different materials are the central topics of spintronics. Different from the electrical charge, the transport of spins does not depend on the electron motion, especially spin can transport without accompanying Joule heating in insulators. Therefore, insulators are looked as ideal materials for spin conductors, in which magnetic Insulators are the most compelling systems.

Recently, we experimentally studied and theoretically discussed spin transport in various antiferromagnetic insulators (AFMIs). It is discovered that the spin susceptibility and the Neel vector are the most important factors affect the transport spin. It is demonstrated that spin current can be a probe for detecting the antiferromagnetic phase transition in an ultra-thin AFMI film[1]. Furthermore, in a uniaxial AFMI material ($Cr_2O_3$), a spin conductor-nonconductor transition is discovered. Such a transition can be tuned efficiently by an external magnetic field, which is reminiscent of the CMR in electronics and named to be SCMR[2].

Reference:
[1] Z. Qiu, et al., **Nat. Commu.** 7, 12670 (2016).
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**Giant spin-orbit torque in a single ferrimagnetic metal layer**

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Antiferromagnets and compensated ferrimagnets offer opportunities to investigate spin dynamics in the 'terahertz gap' because their resonance modes lie in the 0.3 THz to 3 THz range. Despite some inherent advantages when compared to ferromagnets, these materials have not been extensively studied due to difficulties in exciting and detecting the high-frequency spin dynamics, especially in thin films. Here we show that spin-orbit torque in a single layer of the highly spin-polarized compensated ferrimagnet $Mn_2Ru_xGa$ is remarkably efficient at generating spin-orbit fields $\mu_0 H$eff, which approach $0.1\times10^{-10}$ Tm$^2$/A in the low-current density limit – almost a thousand times the Oersted field, and one to two orders of magnitude greater than the effective fields in heavy metal/ferromagnet bilayers. From an analysis of the harmonic Hall effect which takes account of the thermal contributions from the anomalous Nernst effect, we show that the antidamping component of the spin-orbit torque is sufficient to sustain self-oscillation. Our study demonstrates that spin electronics has the potential to underpin energy-frugal, chip-based solutions to the problem of ultra high-speed information transfer.

**Ab-initio antiferromagnetic spintronics: from exotic interactions to novel transport effects**

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In the field of spintronics antiferromagnetic materials steadily move into the focus of attention owing to their unique properties, which range from utter sensitivity to electrical currents [1] to a whole world of possible topological effects rooting in complex real- and reciprocal-space behavior [2]. In my talk I will demonstrate that we can employ advanced *ab-initio* methods to access important characteristics of antiferromagnets (AFMs) such as spin-orbit torques, which ultimately lie at the foundation of our ability to control the AFM order by purely electrical means, and the Dzyaloshinskii-Moriya interaction that can aid us in forming complex real-space textures in the important class of synthetic AFMs [3]. Based on microscopic theory, I will also introduce novel phenomena which are inherent to antiferromagnetic materials, and which bear great promises for their applications. In particular, I will demonstrate that in non-coplanar AFMs there arises a “hidden” orbital order which manifests in what we refer to as topological orbital magnetization [4, 5]. We show that the emergent orbital magnetism should be prominent in many representative AFMs and could be observed with conventional techniques. Moreover, we uncover that the topological orbital magnetism originates from Berry phase properties of electrons hopping on a non-collinear lattice, and it mediates novel exchange interactions [6], able to stabilize an AFM order of given chirality without the need for Dzyaloshinskii-Moriya interaction or an external magnetic field. Based on tight-binding and *ab-initio* analysis, we show that the very same Berry phase effect, promoted in non-coplanar AFMs, not only stands at the foundation of the anomalous Hall effect in this class of materials [2], but also paves the way to a novel family of phenomena in magneto-optics, tagged as topological and quantum topological magneto-optical effects [7]. Possible applications of the latter manifestations of antiferromagnetism will be briefly discussed.

References

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**Effect of Grain Boundaries in Nanomaterials for Radiation Tolerance**

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NON-VOLATILE MEMORIEs (NVMs) are required in a variety of nuclear and space applications for data or code storage. In the past years, a large amount of work has been devoted to studying radiation effects in a wide cross section of commercial NVMs, such as floating-gate, nanocrystals, nanotubes, magnetoresistive and ferroelectric. Designing a nanomaterial from the atomic level to achieve a radiation tolerance in extreme conditions is a grand challenge in memory research. Our investigation is focusing on fundamental understandings of the interactions between point defects and grain boundaries. It was found that important consideration of GBs that quantify the efficiency of a sink to annihilate point defects. This surprising finding provides a novel opportunity to enhance the radiation resistance of nanocrystalline materials through GB engineering. Our atomistic simulation has demonstrated that the GBs have a “loading-unloading” effect that happens from picosecond. Such GBs can serve as effective sinks for radiation-induced defects such as interstitials and vacancies. Upon irradiation, interstitials are loaded into the boundary, which then acts as a source, emitting interstitials to annihilate vacancies in the materials. This unexpected recombination mechanism has a much lower energy barrier than conventional vacancy diffusion and is efficient for annihilating immobile vacancies, resulting in self-healing of the radiation-induced damage. Nanomaterials provide a path to radiation tolerance because GBs that attract, absorb and annihilate point and line defects. Controlling radiation-induced-defects via GBs is shown to be the key factor in reducing the damage and imparting stability in nanomaterials under extreme conditions.

**Above room temperature topological Hall effect in heavy metal/magnetic insulator heterostructures**

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Magnetic skyrmions are topologically-robust nanoscale spin textures that can be manipulated with low current densities and are thus potential information carriers in future spintronic devices. Skyrmions have so far been mainly observed in metallic films, which suffer from Ohmic losses and therefore high energy dissipation. Magnetic insulators could provide a more energy efficient skyrmionic platform due to their low damping and absence of Joule heat loss. However, skyrmions have previously been observed in an insulating compound ($Cu_2OSeO_3$) only at cryogenic temperatures, where they are stabilized by a bulk Dzyaloshinskii-Moriya interaction. Here we report the observation of the topological Hall effect – a signature of magnetic skyrmions – at above room temperature in a bilayer heterostructure composed of a magnetic insulator (thulium iron garnet; $Tm_3Fe_5O_{12}$) in contact with a metal (Pt). The dependence of the topological Hall effect on the in-plane bias field and the thickness of the magnetic insulator suggest that the magnetic skyrmions are stabilized by the interfacial Dzyaloshinskii-Moriya interaction. By varying the temperature of the system, we can tune its magnetic anisotropy and obtain skyrmions in a large window of external magnetic field and enhanced stability of skyrmions in the easy-plane anisotropy regime.

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| 4 | Fengguang Liu | Negative Capacitance Magnetic Tunneling Junctions |
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